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THE SENSITIVITY OF SEVERAL EXPLOSIVES TO IGNITION IN THE LAUNCH ENVIRONMENT

JOHN STARKENBERG
DOENEE L. McFADDEN
DEBORAH L. PILARSKI

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13. ABSTRACT (Maximum 200 words) We have completed testing of the sensitivity of Composition B (Comp B), TNT, Composition A3 (Comp A3) Type II, LX-14, PBXW-113, PBX-0280 and PBX-0280/PE to ignition by the combined effects of air compression and deformation. Comp B exhibits one of the highest sensitivity levels and responds violently. The data for TNT provide no reason to believe that it is less sensitive to ignition than Comp B. Composition A3 Type II may be considered the least sensitive explosive tested. It exhibits a moderately high level of response violence. LX-14 exhibits a sensitivity intermediate between those of Comp B and Comp A-3 Type II and reacts very violently. PBXW-113 is by far the most sensitive in this test. It also produces the mildest response. The sensitivity of PBX-0280 is generally greater than that of Comp B. PBX-280/PE, on the other hand, appears quite insensitive. Our results can be explained most satisfactorily in terms of each explosive's tendency to deconsolidate, or break up into small particles, during cavity collapse.				
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1. INTRODUCTION

Experimental studies aimed at clarifying the mechanisms involved in the premature ignition of high explosives in the launch environment have been pursued for a number of years at the Ballistic Research Laboratory (BRL) ⁽¹⁻⁶⁾. This work was done using an apparatus referred to as the activator. Investigators at the Naval Surface Weapons Center have concentrated on simulating projectile geometries and developing statistical data in a large-scale drop-weight simulator ⁽⁷⁻⁹⁾. This work has not been pursued recently due to the high cost, which severely limits the amount of data that can be collected, and the fact a sufficiently accurate representation of the launch environment is still not obtained. Much of the early work has been summarized by Fishburn ⁽¹⁰⁾. Our investigations have focussed on ignition of explosives due to compression of occluded air, deformation of the explosive during the collapse of included cavities and a combination of these. Boyle and his coworkers have also considered shear under pressure ⁽¹¹⁾.

Results obtained with the activator indicate that none of these mechanisms can ignite explosives at or near nominal launch pressures or pressurization rates. Rather, these parameters must be amplified by about an order of magnitude before ignition is observed. This is to be expected as premature explosions are uncommon. We believe that, when a premature occurs, the explosive is locally subjected to the same stimulus level generated in our experiments. In general, the explosive must be subject to a minimum heating rate per unit surface area if an ignition is to occur. In the case of air compression heating, the heating rate is roughly proportional to the product of the pressurization rate and a representative cavity dimension while the surface area depends on how the cavity collapses. In the case of frictional or shear heating, the heating rate is roughly proportional to the product of the (pressure dependent) viscosity and the square of the shear strain rate. In both cases, many other factors are also important. Pressurization rates and peak pressures measured external to projectile bases or inferred from acceleration histories and explosive column heights appear insufficient to produce the required stimulus. The maximum sliding velocity produced by projectile rotation is somewhat below that required for ignition observed in activator experiments which isolate frictional heating. Amplification of these stimulus levels may occur in a number of ways. In the case of air compression heating, one way is to amplify the pressurization rate. This can occur if a loose charge impacts the base or if a cavity fails to collapse during the early portion of pressurization and then collapses very rapidly when a critical pressure has been reached. A cavity collapse geometry which concentrates heated air on a small portion of the explosive surface also amplifies the stimulus level. In addition, as a cavity collapses, shear heating may combine with air compression heating to produce an ignition.

The relationship between the local heating rate experienced by an explosive fill, the mechanical properties of the explosive and the acceleration history of the projectile is complicated and has not been established. We have not pursued this avenue. Rather, we have tried to determine the parameters which govern ignition by the most likely mechanisms and to develop ignition threshold data for explosives including Composition B (Comp B) and TNT. Vietnam-era field experience has shown that Comp B exhibits a relatively high (usually unacceptable) incidence of in-bore premature explosions while TNT exhibits a relatively low incidence. We felt that the susceptibility of other explosives to premature ignition might be assessed by comparing their ignition thresholds to those of Comp B and TNT. However, the issue is complicated by the fact that the explosiveness of the burning response is also a factor. It has been speculated that the infrequency of reported prematures with TNT may be due to its relatively slow burning response rather than a lower ignitability. This would lead to the premature explosion occurring down range rather than in the gun tube. If this is the case, the sensitivity assessment is more difficult as both ignitability and explosiveness must be considered.

We have recently completed testing of the sensitivity of a number of different explosives to ignition by the combined mechanisms and have used the results to assess their relative sensitivities. Results for Comp B were reported previously ⁽⁴⁶⁾. Additional explosives tested include TNT, Composition A3 (Comp A3) Type II, LX-14, PBXW-113, PBX-0280 and PBX-0280/PE. In this report, we discuss the pertinent ignition mechanisms, describe the experimental approach, review some the early activator results, compare the data obtained for all of the explosives and provide an interpretation of the observations.

2. IGNITION MECHANISMS

2.1 Gas Compression. When a small volume of air is compressed very rapidly such that no energy transport can occur, a high temperature reservoir is created which may subsequently heat an adjacent explosive layer to the point of ignition. This process is referred to as ignition by adiabatic compression of the air. If, on the other hand, the air is compressed very slowly, no temperature increase occurs and no explosive ignition can follow. Between these limits lies the compressive heating regime in which the compression occurs sufficiently slowly that considerable energy is transported by conduction and convection during the process. The ignitions observed by Bowden and his associates in the ten- to hundred-microsecond time range properly belong to this latter

category ⁽¹²⁾. For adiabatic compression in the shock wave regime, the heating due to gas compression does not appear to influence sensitivity since other heating mechanisms dominate ⁽¹³⁻¹⁵⁾. Compressive heating has, therefore, received attention primarily as a source of ignition which is active when the observed time to ignition is in the ten-microsecond to ten-millisecond range, a time scale which is typical of events during the setback of the explosive fill in a projectile during launch.

2.2 Shear. The shear mechanism has also received considerable attention. This mechanism is active when shearing flows are produced by cavity collapse or by motion relative to a surface such as the interior of the projectile casing. These flows tend to localize deformation in shear bands leading to the production of high local temperatures as discussed by Frey ⁽¹⁶⁾. The action of friction under pressure (in the absence of air compression) has been considered by Boyle ⁽¹¹⁾. Our earlier results show that this mechanism is also active during cavity collapse but that air compression is usually the dominant mechanism ^(4,6).

3. DESCRIPTION OF THE EXPERIMENTS

3.1 The Activator. The experimental investigation was conducted using an apparatus, referred to as the activator, which was originally designed at Picatinny Arsenal for use as a laboratory-scale artillery setback simulator ⁽¹⁷⁾. The activator, as presently used at BRL, is illustrated schematically in Figure 1. The test section consists of a 63.5-mm (2.5-in.) diameter mild steel, heavy confinement cylinder with a 12.7-mm (.5-in.) diameter bore hole enclosing the explosive sample and a hardened steel driving piston. A hardened steel gauge block on which a manganin foil pressure gauge is mounted is tightly bolted to the back of the confinement cylinder and the explosive sample is inserted into the bore adjacent to the gauge. A gap or cavity of some type is formed adjacent to or in the end of the sample. The gauge block rests against a rigid stop which incorporates an adjustment screw to accommodate test fixtures of different lengths and to allow easy installation. The driving piston is activated by a larger piston which is initially held in place using shear pins. The large piston is set in motion by pressure developed in the breech which is instrumented with a pressure transducer. The free run allowed between the large piston and the driving piston is used to set the stimulus level to be applied. In order to conduct a test, the breech is pressurized using compressed air until the shear pins fail. The large piston accelerates through the free run and impacts the driving piston. The momentum developed by the pistons is transformed to an impulse

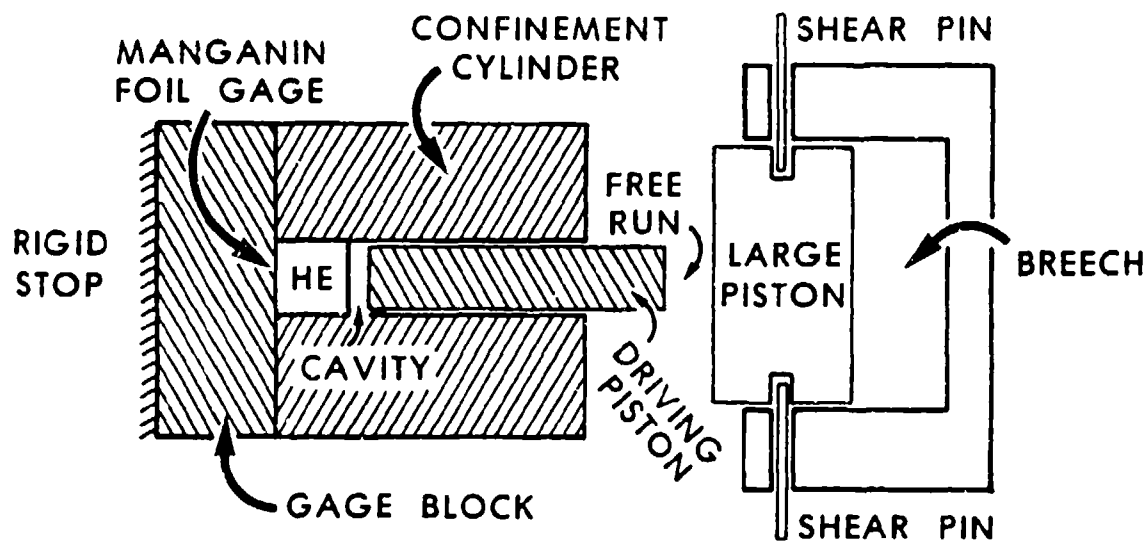


Figure 1. Activator Schematic.

delivered to the sample. This impulse is as much as 0.6 GPa in amplitude and approximately 0.5 ms in duration, producing an average pressurization rate as high as 2.5 GPa/ms. The pistons may then rebound and strike the explosive again delivering a second, smaller, impulse. The breech pressure begins at the shear pin failure pressure and drops linearly with time during the test to a value associated with the final volume of the breech.

A disadvantage of this test configuration is that extrusion of explosive between the gauge block and the confinement cylinder may occur at the higher free runs because the loading action tends to increase the space there. Extrusion of explosive between the driving piston and confinement cylinder is avoided by maintaining tight tolerances on the clearance. Ignitions caused by extrusion are sometimes identifiable as late events on the pressure records. Extrusion ignition is an artifact of the experimental procedure which is not relevant to ignition in the launch environment. Generally, there exists a free run below which extrusion does not occur. Our experience indicates that testing with solid samples to determine this free run is advisable. Determination of ignition thresholds due to cavity collapse at lower stimulus levels is then possible. This procedure was followed for all the explosives we tested except Comp B and TNT.

3.2 Bubble Tests. An early version of our test procedure (which is no longer used but from which we learned a number of important things which are reviewed in this report) is called the bubble test. It is illustrated schematically in Figure 2. In this test, the cavity, a hemispherical "bubble", was cast into one end of a piece of Dow Corning Sylgard 182 which was then placed in contact with the flat surface of the explosive sample. Sylgard bubbles and Comp B samples are shown in Figure 3. This provided a cavity external to the explosive in a material which behaves essentially like an inviscid fluid under activator loading. The heating of the explosive due to the compression of the air in the bubble is directly related to the rate of pressurization.

3.3 Dimple Tests. The dimple test, of which there are three variations, is the procedure currently in use. The experimental configuration for each is shown schematically in Figure 4. In the standard dimple test, a cylindrical cavity or "dimple" of controlled depth and diameter is cast or machined into one end of the explosive sample. The sample is inserted, dimple up, into the confinement cylinder. A thin polyethylene film attached to the face of the driving piston improves the seal against the face of the explosive sample. In another variation, vacuum hardware is used. Prior to firing, the piston is inserted into the bore hole but held away from the sample until sufficient vacuum has been produced using a vacuum pump. The piston is then allowed to move forward against the sample, sealing a vacuum into the dimple. The vacuum pump continues to operate until after the firing is completed. In a third variation, the dimple is cast into a piece of Sylgard (as in the bubble test). This is then placed in contact with an undimpled explosive sample. All other test procedures are as previously described. In the vacuum dimple test, only deformation heating can produce an ignition. In the Sylgard dimple test, only air compression heating occurs. Both heating mechanisms are combined in the standard dimple test.

3.4 Sample Preparation. Comp B samples and Sylgard dimples used in the dimple test series are shown in Figure 5. Dimples begin at a nominal depth of 0.38 mm (.015 in.) and increase in steps of 0.38 mm to a maximum depth of 1.91 mm (.075 in.). The actual depths vary somewhat from the nominal values and must be measured. Dimple diameters of 6.4 mm (.25 in.) and 8.6 mm (.34 in.) were used in testing Comp B. Only 6.4-mm diameter dimples were used in testing of all the other explosives. All explosives reported on have been subjected to the standard dimple test. Only Comp B has also been subjected to Sylgard and vacuum testing as reported previously ⁽⁴⁶⁾.

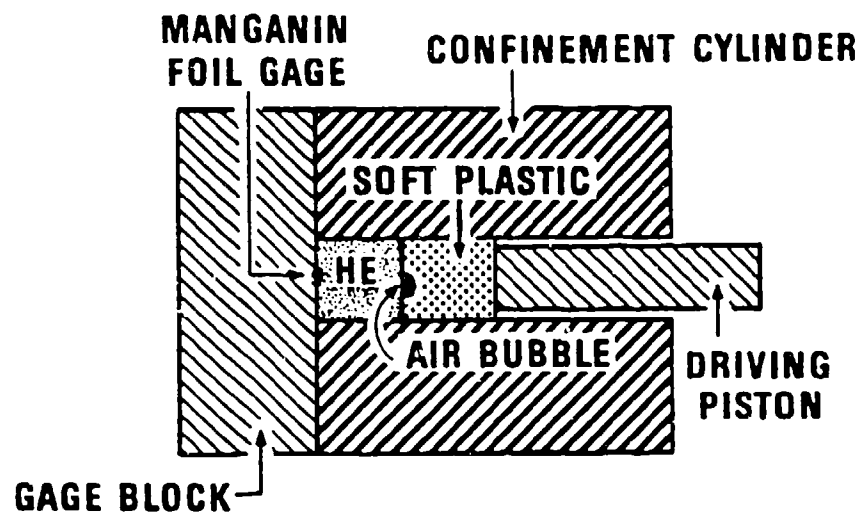


Figure 2. Bubble Test Schematic.

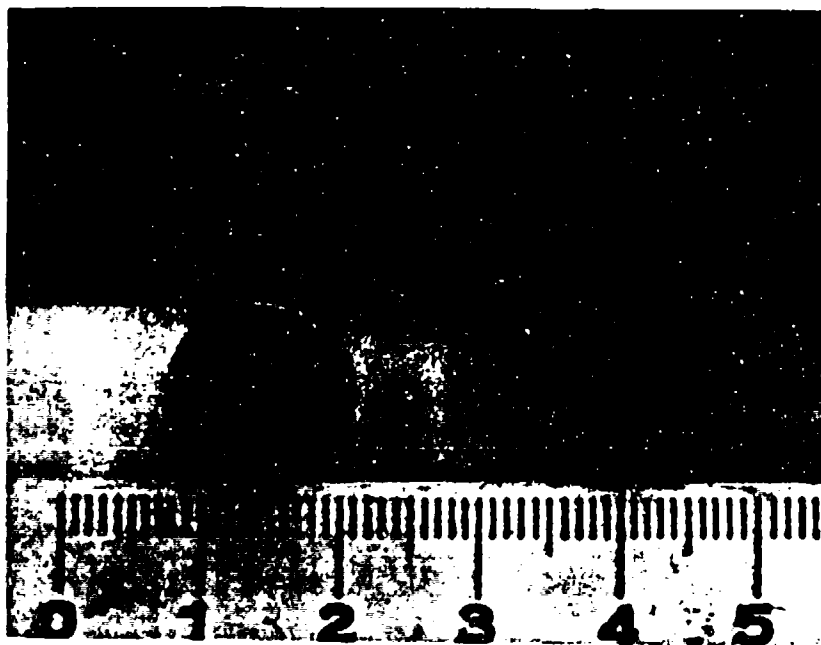


Figure 3. Sylgard Bubbles and Explosive Samples.

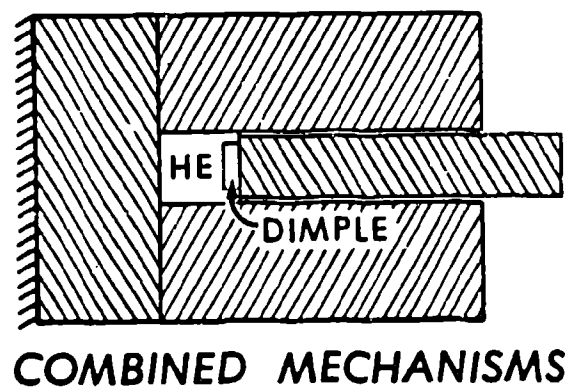
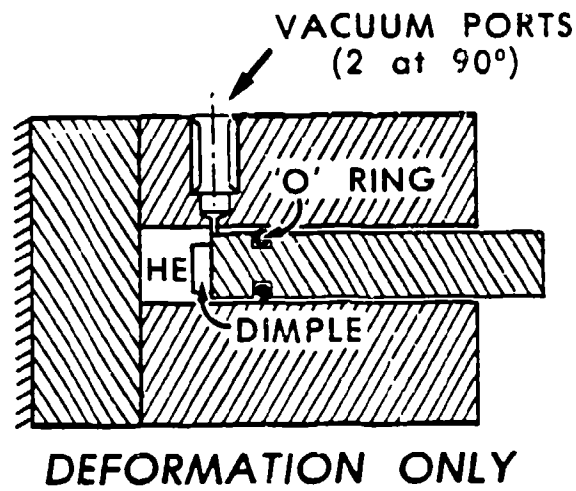
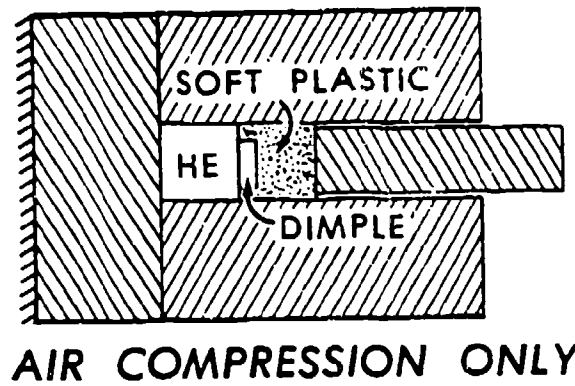


Figure 4. Dimple Test Series Schematics.



Figure 5. Dimpled and Undimpled Composition B Samples and Sylgard Dimples.

The Comp B and TNT samples were prepared at BRL by casting short 12.7 mm diameter cylinders. In order to prepare dimpled samples, a casting plate with cylindrical protrusions of adjustable height was used beneath the mold. For undimpled samples, a flat polished casting plate was used. All samples were finished to a length of 12.7 mm by cutting and polishing the opposite end.

The LX-14, Comp A3 Type II and PBXW-113 samples were prepared by Honeywell, Inc. The PBX-0280 and PBX-0280/PE samples were prepared at Picatinny Arsenal. Dimples in these samples were produced by machining. Other details of their preparation are unknown.

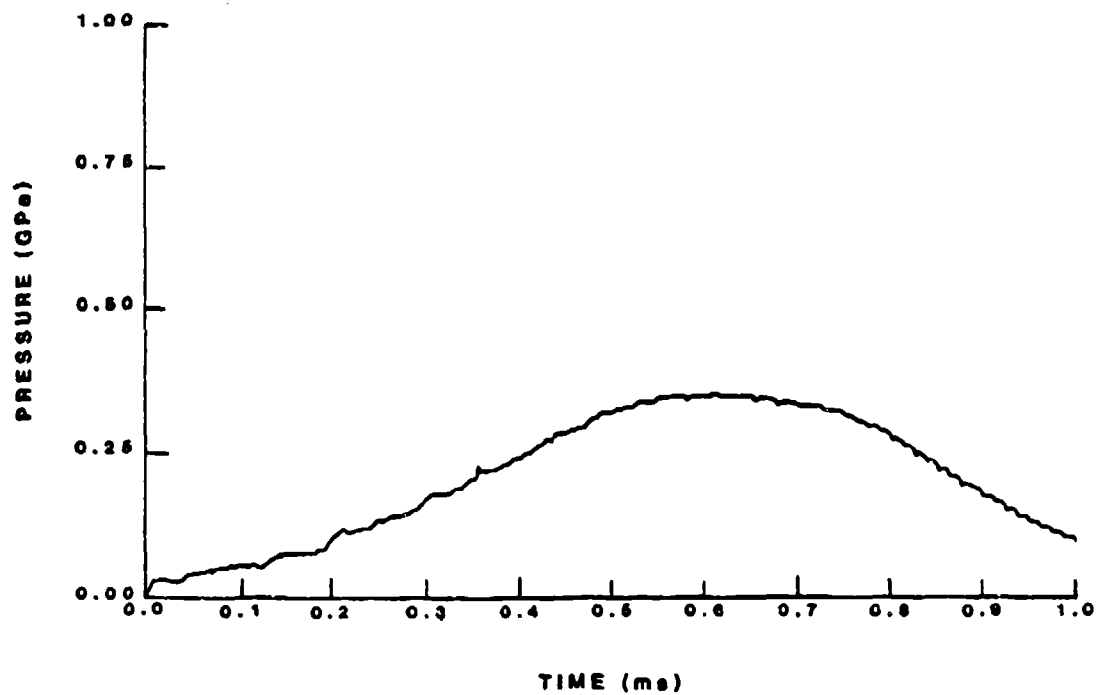
Sample dimensions, including dimple depth and diameter, and sample weight were measured and the density of each sample was computed. All samples were inspected radiographically and any sample appearing to have internal voids was rejected.

The unclassified formulations and the average percentages of theoretical maximum density (TMD) of the explosive samples tested are summarized in Table 1.

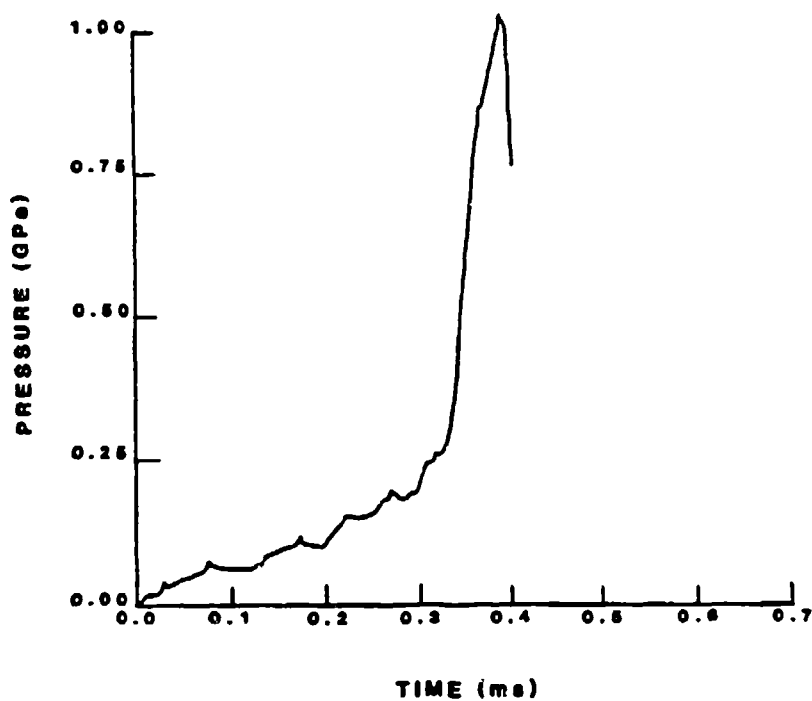
Table 1. Summary of Explosive Formulations.

	% TNT	% RDX	% HMX	% ESTANE	%POLY- ETHYLENE	AVERAGE % TMD
TNT	100	-	-	-	-	96.6
Comp B	40	60	-	-	-	97.9
Comp A3 Type II	-	91	-	-	9	98.4
LX-14	-	-	95	5	-	97.0
PBX-0280	-	95	-	5	-	96.8
PBX-0280/PE	-	95	-	-	5	96.5

3.5 Characterization of the Stimulus Level. In our earlier tests with cavities external to the explosive, pressure conditions in the vicinity of the cavity could be inferred from the pressure records from the manganin gauge at the base of the sample. Typical pressure records are shown in Figure 6. This provided us with a pertinent characterization of the stimulus level. In the dimple test, however, the conditions as the cavity collapses are complicated and the heating rate bears no simple relation to the pressure record. The best measure of applied stimulus level must be judged, therefore, by the degree to which it segregates ignitions and ignition failures in a plot of stimulus level versus cavity size. Several measures of stimulus level are available. The simplest of these is the free run of the activator. The stimulus generally increases with increasing free run. Since the breech pressure at which the shear pins fail varies somewhat from test to test, the impact momentum may be calculated from the free run and the shear pin failure pressure, providing a second measure of stimulus level which should be an improvement over the free run. Finally, information from the manganin gauge record can be used. In this case, the problem of what aspect of the pressure record to use arises. Peak pressure cannot be used since the occurrence of an ignition before peak pressure is achieved obscures this information. Analysis and experience have taught us that the pressurization rate gives a good indication of the stimulus level. However, the pressurization rate is observed to vary during the test, exhibiting several peaks of approximately the



a) Ignition Failure



b) Ignition

Figure 6. Typical Manganin Gage Pressure Records for Activator Test with Cavities External to the Explosive Sample.

is the only parameter producing good data segregation in all three tests ^(4,6). Thus, results of activator testing are usually given as an ignition threshold in the free run - dimple depth plane.

4. OBSERVATIONS FROM PREVIOUS STUDIES

4.1 Compressive Heating. Compressive heating ignition has been the subject of extensive analytical ^(1,2) and experimental ^(2,3,5) study at BRL. In this work, cavities external to the explosive in a soft material were used. The activator was used in its original form in preliminary experiments to produce data which revealed the role of air in causing ignitions during compression. Subsequently, the activator was modified and further instrumented so that more definitive data could be extracted from the tests and direct comparisons to the predictions obtained from analytical models could be made. In particular, the activator was used to explore ignition of Comp B, TNT and LX-14 (as well as a number of other explosives) caused by the rapid compression of air trapped in contact with the explosive.

A number of observations from our study of air compression heating are pertinent to the present study. As a result of our earlier testing, we learned that this is indeed a viable mechanism for ignition at relatively mild stimulus levels and we established pressurization rate and cavity size as the principal governing parameters. We found that sensitivity is substantially influenced by the geometry of cavity collapse and by the state of the explosive surface. Convergent geometries, such as the hemispherical bubbles, which concentrate heated air on a small portion of the explosive surface, promote ignition. A series of tests with LX-14 pressed to different densities showed that nonporous surfaces also promote ignition by enhancing retention of heated air at the ignition site. This result is illustrated by the ignition threshold curve in the plot of free run versus initial density in Figure 7. The late ignitions shown in the plot occurred on the second strike and may be regarded as artifacts of the experimental procedure.

4.2 Cavity Collapse Heating. In the earliest work, care was taken to completely decouple the local stimulus level from the explosive mechanical properties by using cavities external to the explosive which collapse without its mechanical failure. Subsequently, we turned our attention to a series of experiments in which shallow cylindrical cavities (dimples) in cast Comp B were subjected

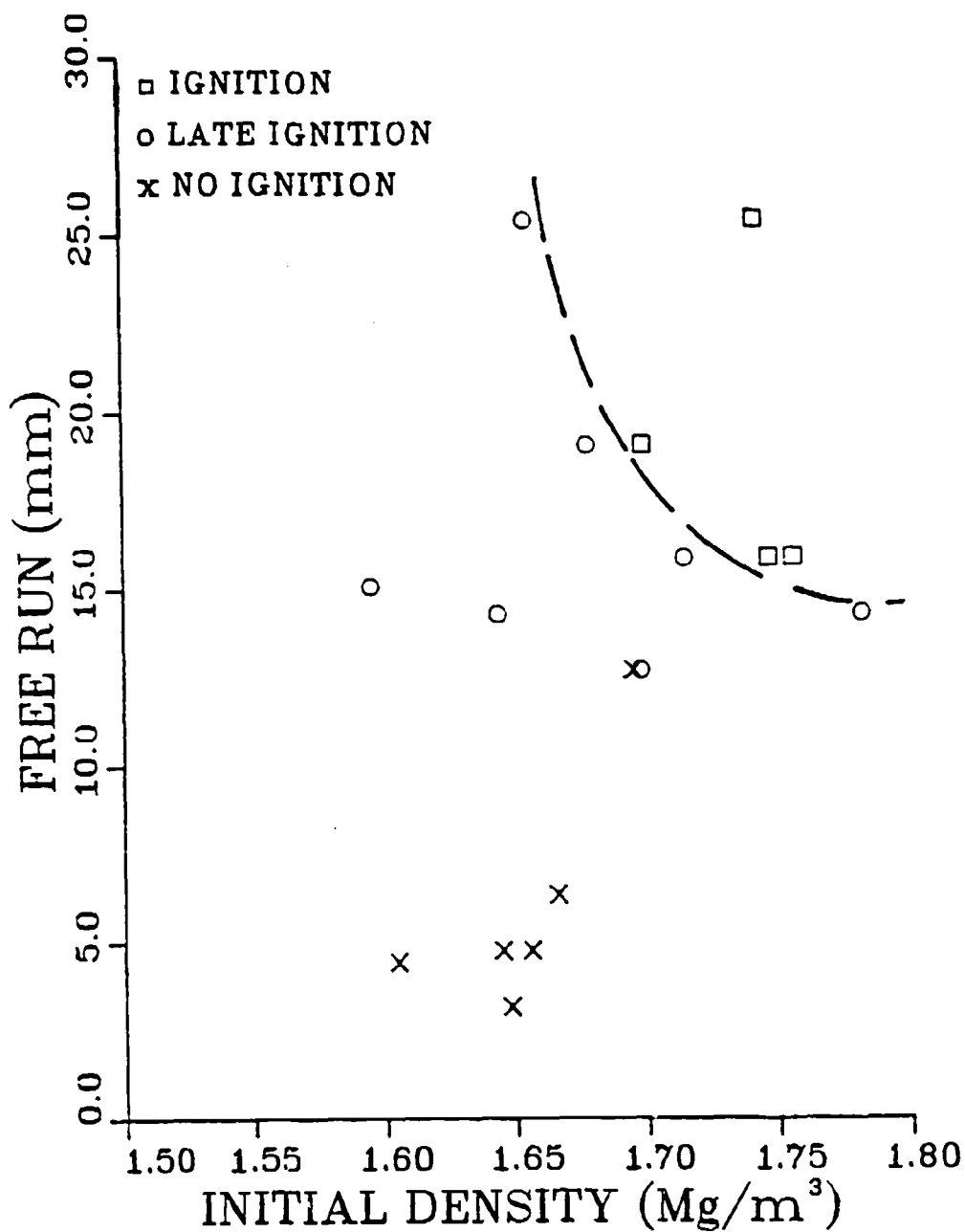


Figure 7. Effect of Initial Pressing Density on the Sensitivity of LX-14 to Ignition in the Bubble Test.

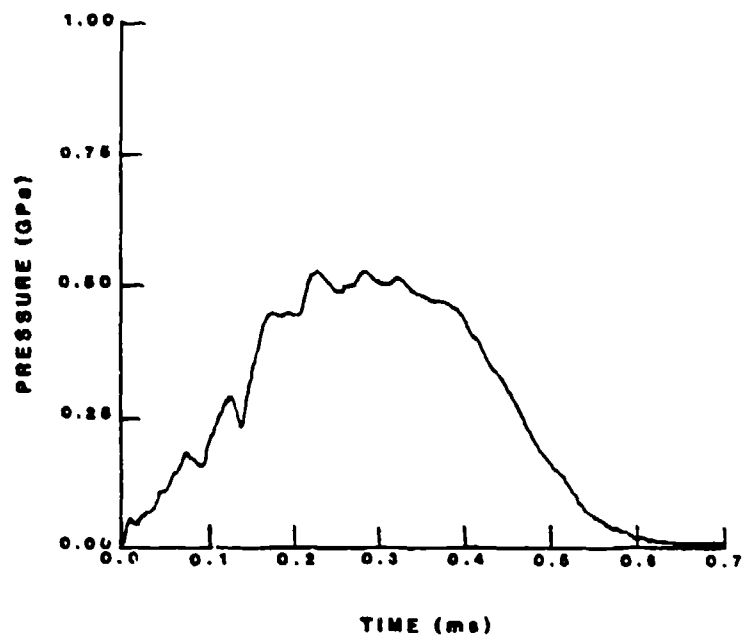
to deformation both with and without simultaneous air compression as well as air compression without deformation. This series of tests was used to explore the role of explosive deformation in ignition ^(4,6). In particular, we were interested in determining whether deformation produces

sufficient heating to cause ignition or simply acts to increase the local air pressurization rate. This approach, of course, does not account for the complete role of explosive mechanical properties in the actual launch environment.

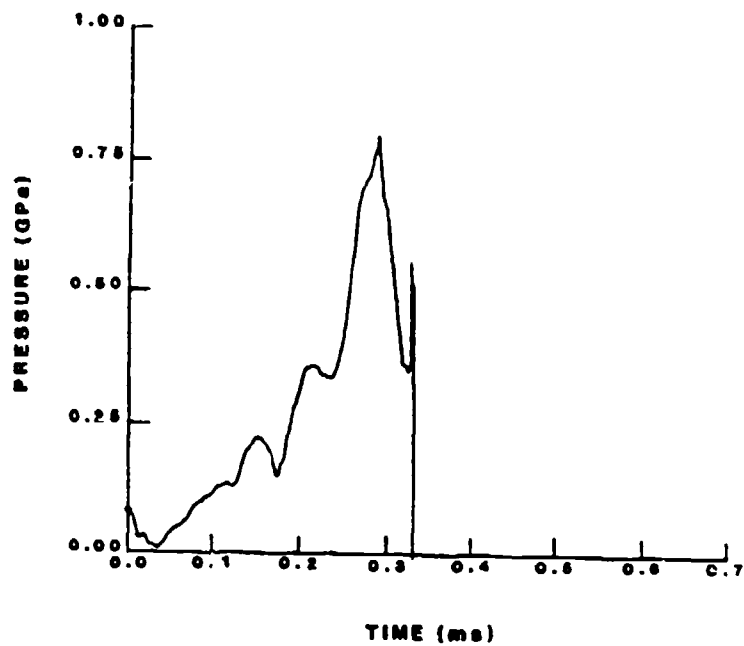
We found that when the air compression and deformation heating mechanisms are combined the dominant ignition mechanism is compressive heating of air strongly influenced by the cavity collapse geometry and by alteration of the state of the exposed explosive surface during collapse. This result is in agreement with Frey's theoretical assessment ⁽⁸⁾, which indicates that the air compression mechanism dominates for large cavities at low pressurization rates. Comp B seemed to exhibit a "maximum tolerable" dimple depth below which ignitions could not be obtained. The observations suggest that the cavity in the explosive may close in at least two different ways depending on dimple depth. Cavity closure for shallow dimples presumably occurs by axial flow and results in low sensitivity. The sudden transition above the maximum tolerable dimple depth observed in the tests was interpreted as marking a transition to radial cavity closure, a highly sensitive mode for which dimple depth independence would be expected. Our compressive heating results indicated that increasing surface porosity leads to decreased sensitivity. One would expect the brittle explosives to break up into particles during cavity collapse, thus reducing sensitivity. The presence of particles can also be sensitizing if they are fine enough. This occurs when the nominal diameter of the particles is less than twice the thickness of the heated explosive layer. However, our planar computations showed that this heated-layer thickness is 25 μm or less when ignition occurs ⁽⁴⁾. Thus, the sensitizing effect should not be expected to appear unless a significant number of particles are 50 μm or less in diameter. Results from tests conducted under vacuum indicate that heating due to deformation alone is the dominant ignition mechanism only for relatively deep dimples.

5. RESULTS

5.1 General Observations. The pressure histories observed may be generally categorized according to the nature of the rising portion of the impulse. When undimpled samples were used the pressure was observed to rise in a series of steps as shown in Figure 6. The pressurization rate between the plateaus was roughly the same. With dimpled explosives, however, the pressure was frequently observed to rise and fall quite markedly during pressurization as shown in Figure 8. The pressure was usually seen to drop back, after a short pressurization, to a considerably lower value



a) Ignition Failure



b) Ignition

Figure 8. Typical Manganin Gauge Pressure Records for Dimple Tests.

before continuing to rise to its maximum. This occurred for both ignitions and ignition failures and is probably associated with cavity collapse. Samples that were recovered after firing almost always showed the dimple to be completely closed. Comp B samples before and after testing are compared in the photograph in Figure 9.

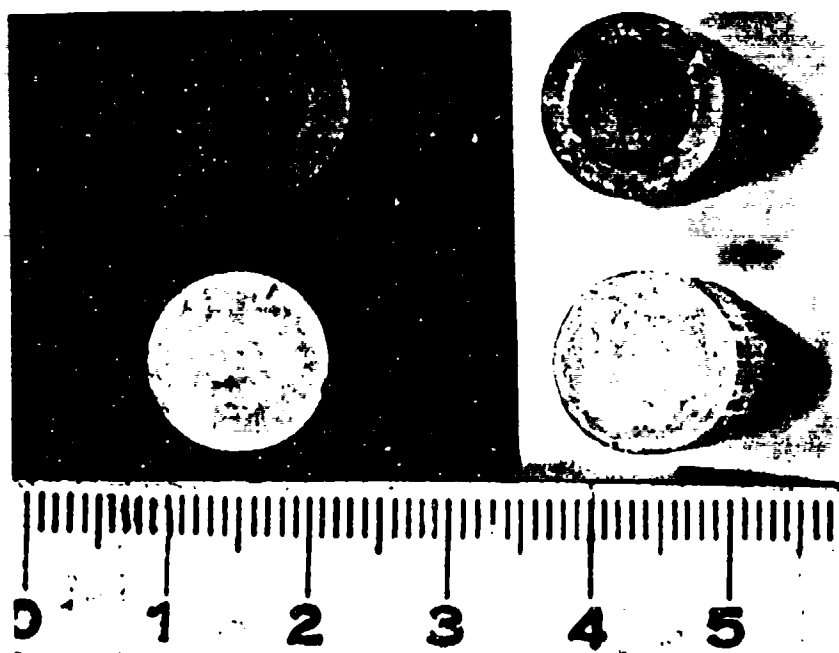


Figure 9. Comparison of Dimpled Composition B Samples Before and After Testing.

Burning may begin during the rising portion of the pressure history, be delayed until after the pressure has peaked, be delayed until much later when the pressure has returned to ambient or occur on the second strike of the driving piston. Where possible, ignitions have been classified as either prompt (when they occur during the stimulus impulse) or late (when they occur substantially after the stimulus impulse). In a few cases, when the pressure record was lost and an ignition clearly occurred, the result is identified simply as an ignition.

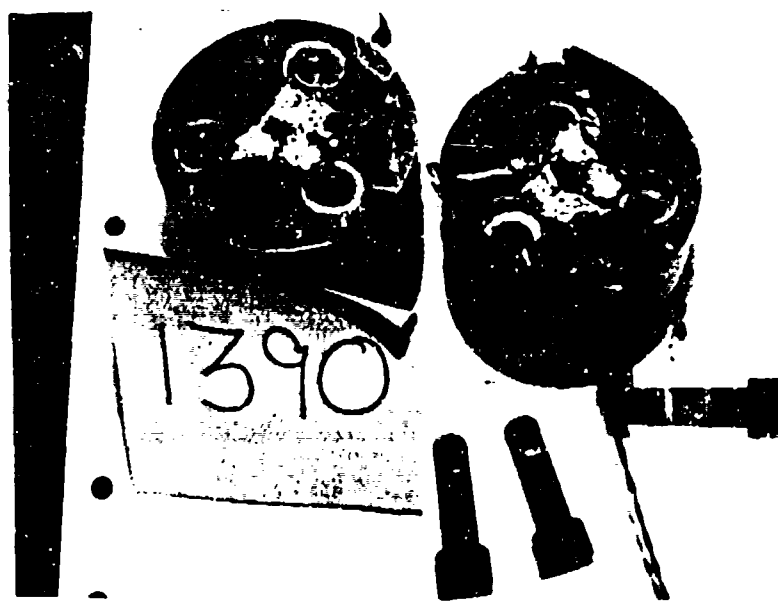
As described in the following sections, we believed that Comp B and TNT were sometimes igniting due to extrusion between the gauge block and the confinement cylinder. Because of this, we decided to screen the subsequently tested explosives using undimpled samples, which are assumed to be ignited only by extrusion.

The violence of reactive responses varied from explosive to explosive and ranged from partial reaction with recovery of significant amounts of explosive to extremely rapid reaction characterized by the splitting of the confinement cylinder into several pieces. These results have been associated with response levels in Table 2. Recovered test hardware at each level is shown in Figure 10.

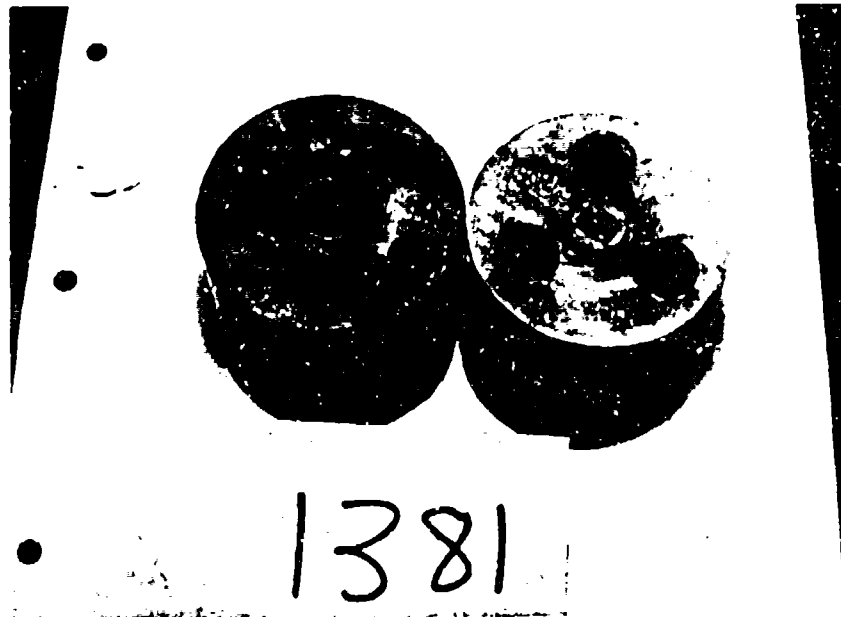
Table 2. Response Violence Levels.

Level	Response Violence
1	Partial reaction. Partially burned explosive sample is recovered or unburned explosive is extruded past gauge block.
2	Complete reaction. Damage to confinement cylinder limited to enlargement of bore hole.
3	Complete reaction. Confinement cylinder split open.
4	Complete reaction. Confinement cylinder split into two or more pieces.

5.2 Composition B. Results for Comp B with two different dimple diameters were previously reported ⁽⁴⁾. The 8.6-mm diameter dimples are considered too large to eliminate substantial influence of the sample diameter. Therefore, testing of other explosives was limited to the 6.4-mm diameter dimples. The data for the smaller diameter is reproduced in Figure 11. No tests on solid samples to determine the extrusion limit were conducted. However, late ignitions (of the type usually associated with extrusion) were observed with shallow dimples at free runs exceeding 22 mm. Two threshold curves have been indicated on the plot in the dimple depth - free run plane. Only ignitions were observed above the upper curve and only ignition failures were observed below the lower curve. A region of mixed results lies between the curves. The results indicate that extremely high stimulus levels are required to produce ignition with the shallowest dimples. The free run required drops rapidly with increased dimple depth until a minimum is reached. Surprisingly, further increase in the dimple depth appears to reduce sensitivity. This behavior allows us to roughly define a maximum tolerable dimple depth at about 0.5 mm, below which ignition requires very high stimulus levels, and a maximum tolerable stimulus level at about 10 mm free run, below which no ignitions occur. When Comp B ignited, the response was fairly



a) Level 1. Partial Reaction. Partially burned explosive sample is recovered or unburned explosive is extruded past gauge block. Note explosive in bolt threads.

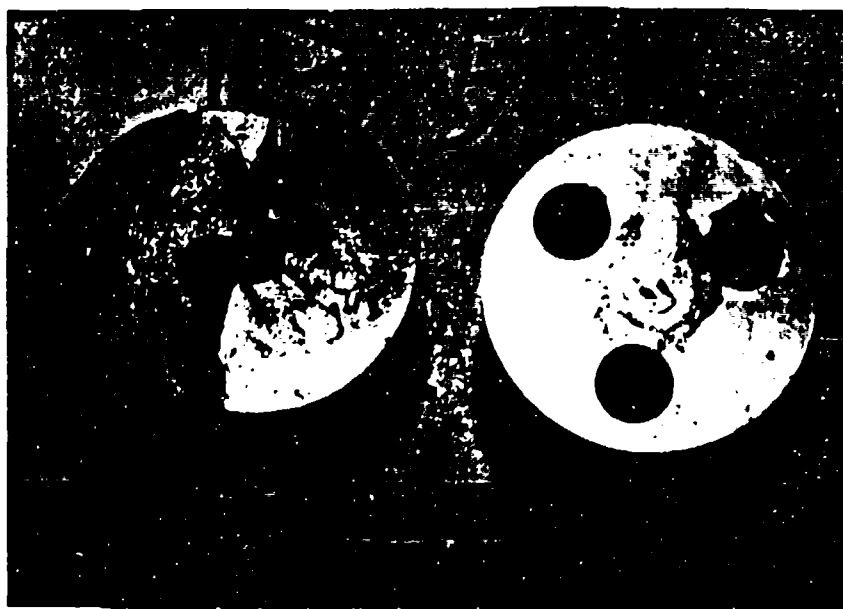


b) Level 2. Complete Reaction. Damage to confinement cylinder limited to enlargement of bore hole.

Figure 10. Activator Hardware Damage Associated with Each Reaction Violence Level.



c) Level 3. Complete Reaction. Confinement cylinder split open.



d) Level 4. Complete Reaction. Confinement cylinder split into two or more pieces.

Figure 10. Activator Hardware Damage Associated with Each Reaction Violence Level. (Continued)

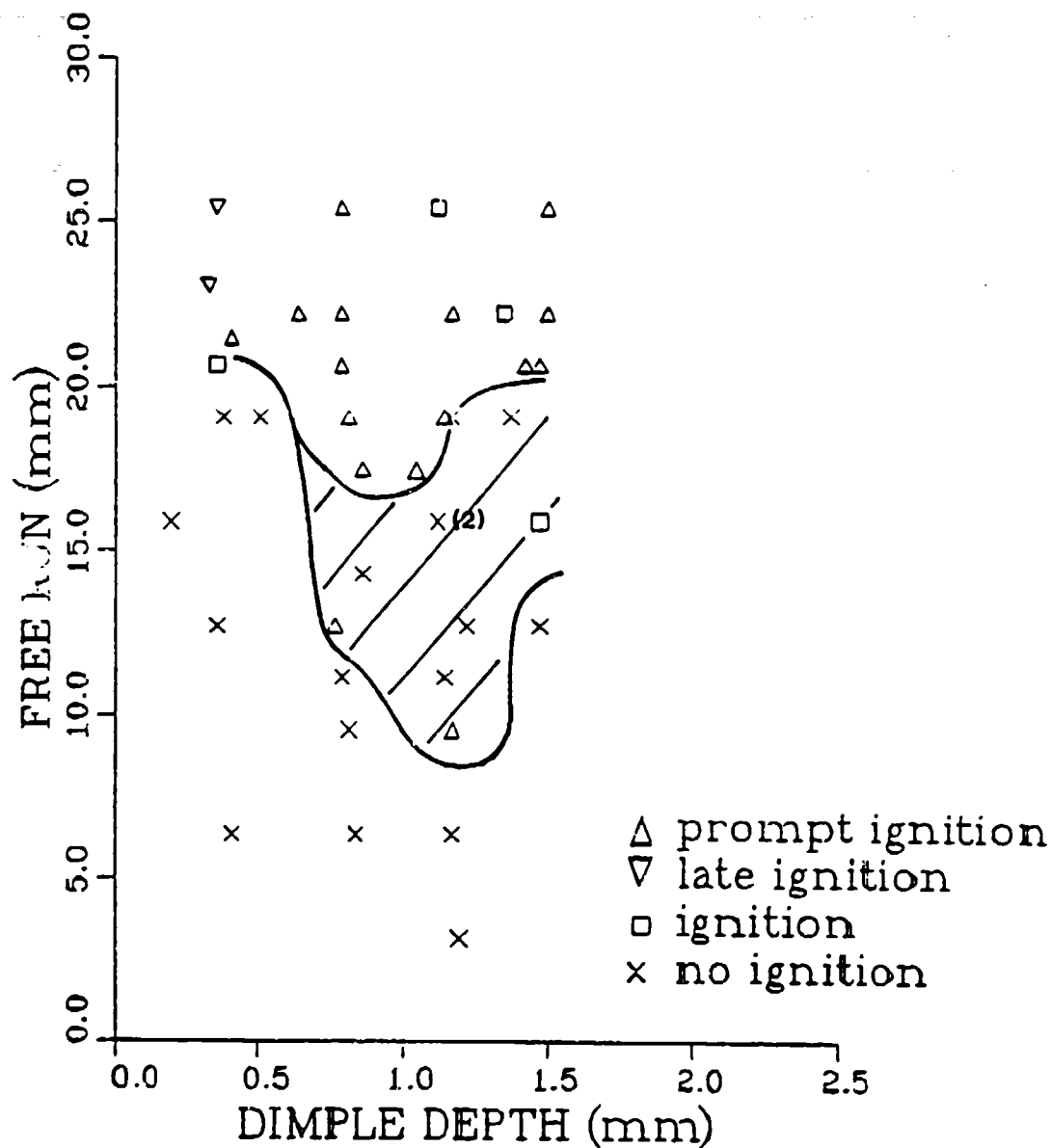


Figure 11. Ignition Threshold for Composition B in the Dimple Depth - Free Run Plane.
Duplicate data points are indicated by (2).

violent, often splitting the cylinder. Several of the samples which failed to ignite were recovered and sectioned as illustrated in the photograph of Figure 12. The cavities were observed to be filled with porous explosive which, for dimples deeper than about 0.4 mm, apparently originated in the shoulder of the dimple. In addition, cone-shaped regions of deformation were observed below the floors of the dimples. The shallowest dimples, on the other hand, were observed to close from the

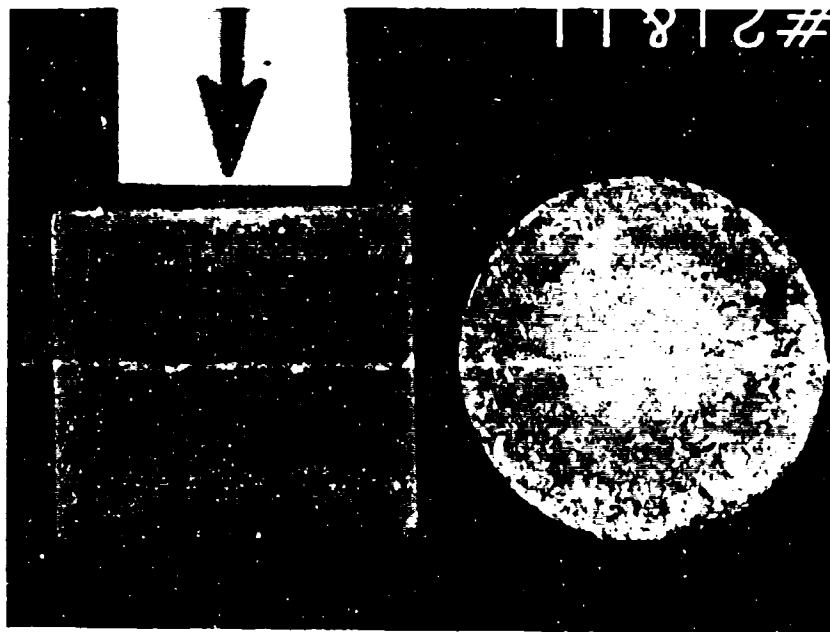
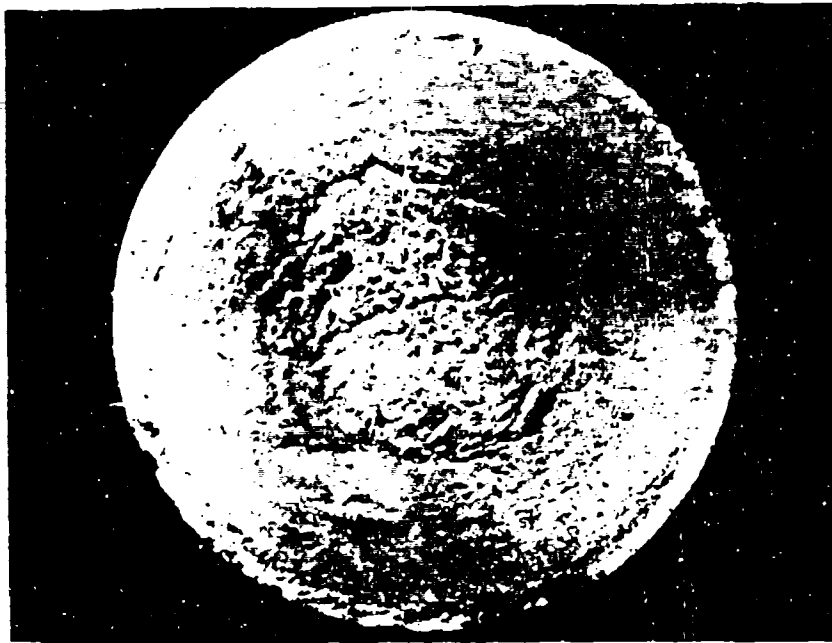


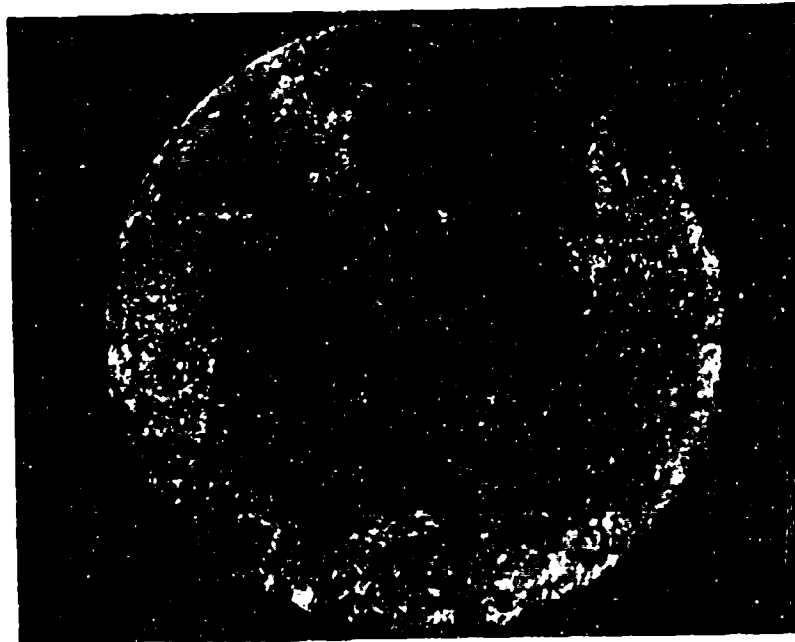
Figure 12. Recovered Composition B Samples. Cross-section and top views.

bottom up. This transition of cavity closure mode is believed to account for the rapid change of sensitivity observed as the dimple depth is reduced to its smallest values. There may be some other such transition which accounts for the decrease in sensitivity for the deepest dimples.

5.3 TNT. We experienced considerable difficulty in obtaining definitive data for TNT and a broader variety of responses was observed. Virtually all ignitions occurred slightly after peak pressure had been reached. In several cases, reaction was extinguished leaving partially burned samples as shown in Figures 13 and 14. In many cases in which incipient reaction was extinguished, burning was observed to begin at the circumference of the dimple. In other cases, at moderate free runs, the samples appeared to melt and extrude past the gauge block without any evidence of reaction. These responses are represented in the plot shown in Figure 15. It is difficult to distinguish ignition, failure and mixed regions as with Comp B. Unfortunately, no rapid decrease in the free run required to produce ignition as dimple depth increased may be observed (probably because no tests were conducted with the shallowest dimples) so that no effective maximum tolerable dimple depth can be determined. However, no ignitions were produced at free runs less than about 12 mm. TNT is known to have a relatively low intrinsic reaction rate. The

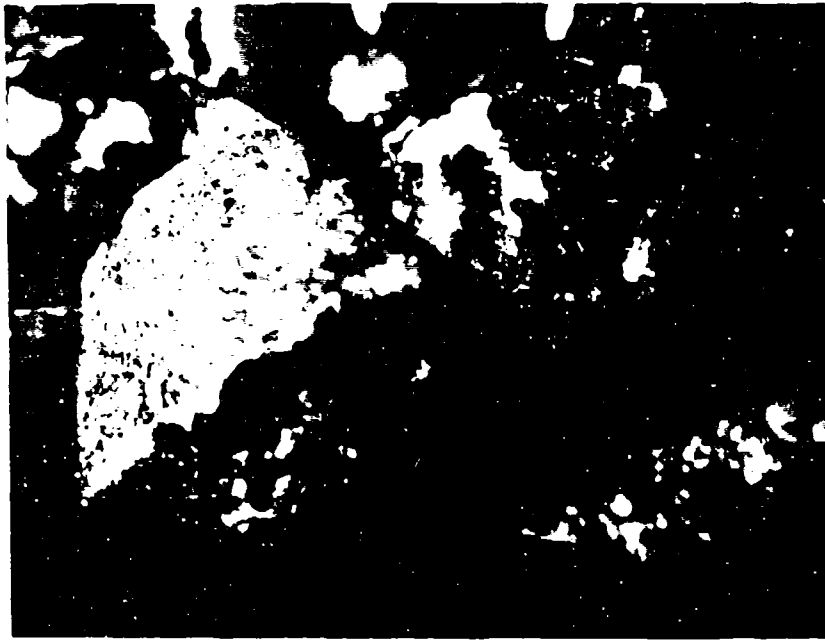


a) 6.4-mm Free Run



b) 17.5-mm Free Run

Figure 13. Recovered TNT Samples. Dimple Depth was 1.14 mm.

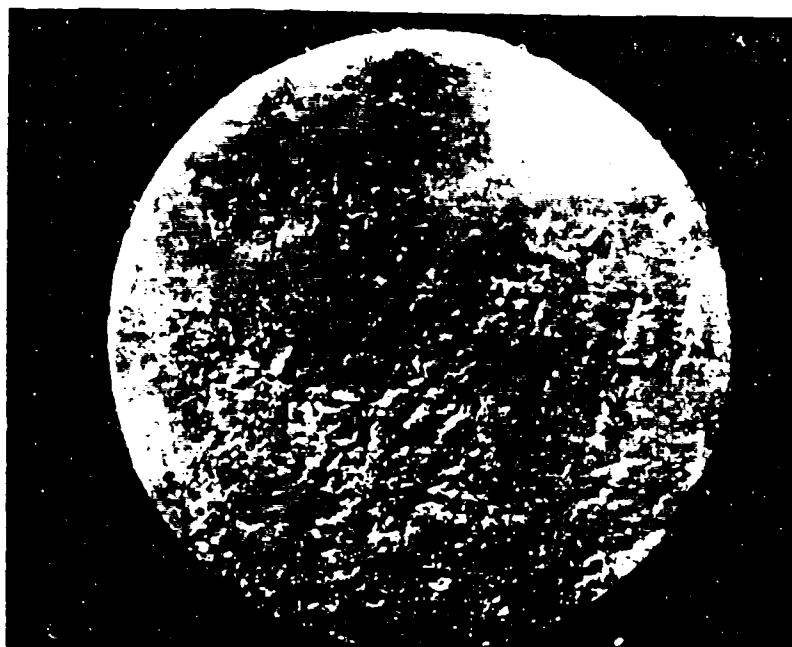


c) 25.4-mm Free Run

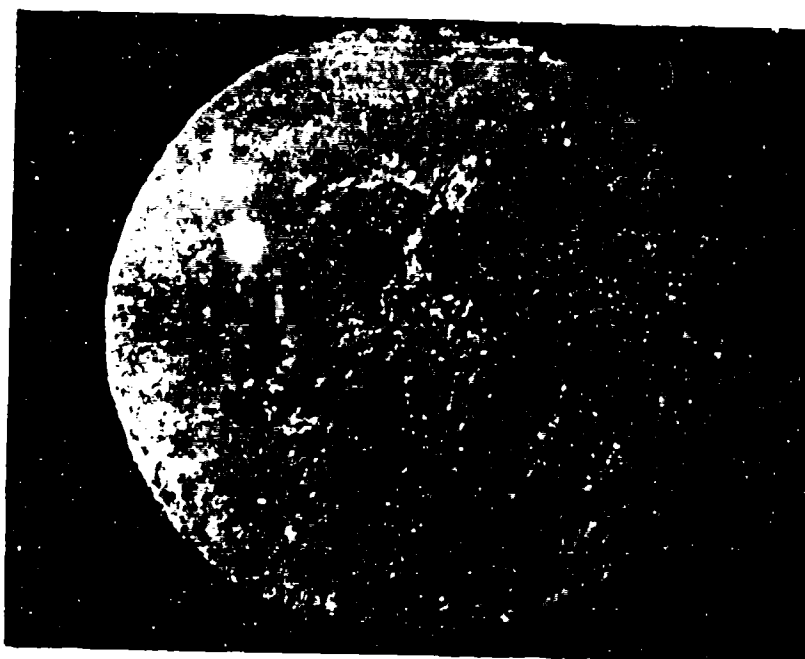
Figure 13. Recovered TNT Samples. Dimple Depth was 1.14 mm. (Continued)

activator's stimulus duration may be too short to appropriately test such a slow burning explosive. The response violence was considerably lower with TNT and the confinement cylinders were not observed to split.

5.4 Composition A3 Type II. Using undimpled Comp A3 Type II samples, we found that extrusion ignition occurred at free runs greater than 20 mm. Fewer tests were conducted than with Comp B or TNT but the ignitions and failures segregate nicely in the dimple depth - free run plane as shown in Figure 16. The maximum tolerable dimple depth is about 1.1 mm but no minimum in required stimulus level is realized. Response violence was greater than that of Comp B and the cylinder was usually split, sometimes into two pieces. Recovered samples at several different dimple depths are shown in Figures 17 and 18. In some cases, the shallowest dimples did not close, even at moderate free runs. This was not observed with any other explosive. The photographs suggest a possible cavity collapse mode transition between dimple depths of 1.1 mm (corresponding to the maximum tolerable dimple depth) and 1.5 mm.



a) 12.7-mm Free Run



b) 14.3-mm Free Run

Figure 14. Recovered TNT Samples. Dimple Depth was 1.91 mm.



c) 15.9-mm Free Run



d) 17.5-mm Free Run

Figure 14. Recovered TNT Samples. Dimple Depth was 1.91 mm. (Continued)

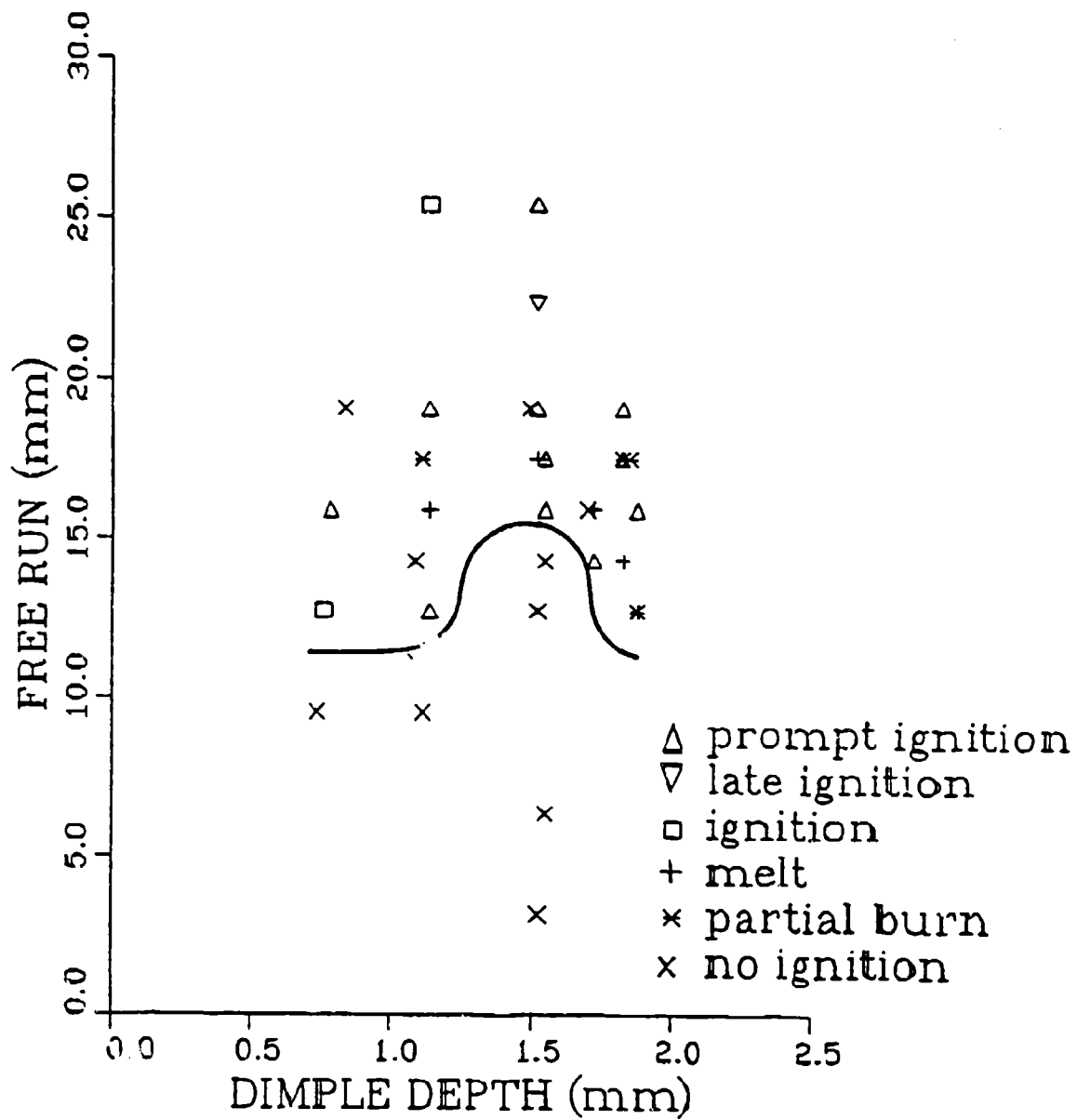


Figure 15. Ignition Threshold for TNT in the Dimple Depth - Free Run Plane.

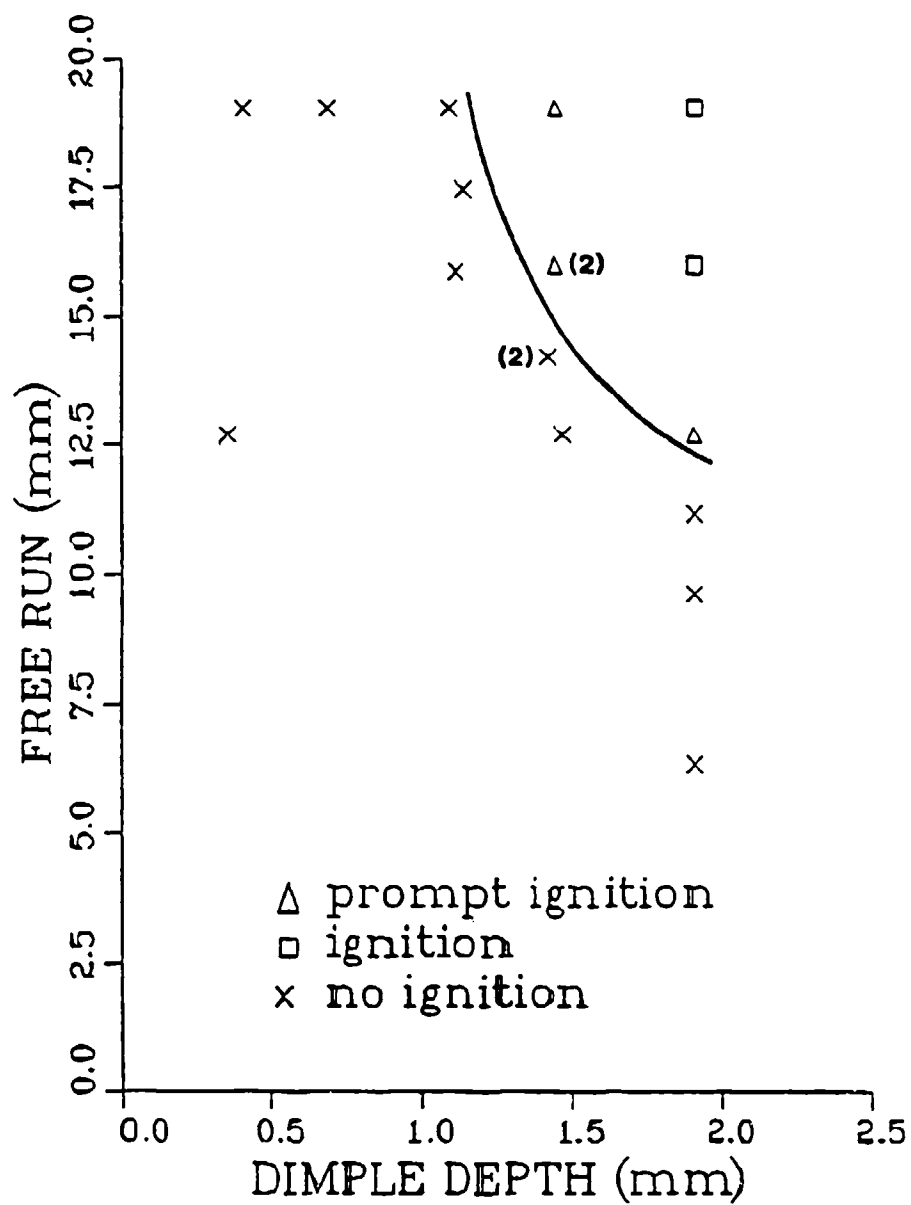


Figure 16. Ignition Threshold for Composition A-3 Type II in the Dimple Depth - Free Run Plane. Duplicate data points are indicated by (2).

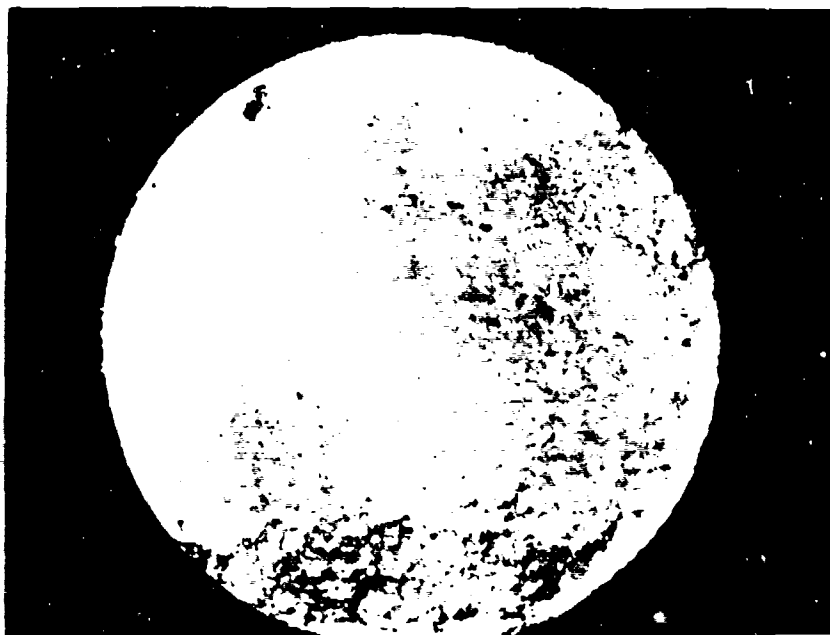


a) Top View

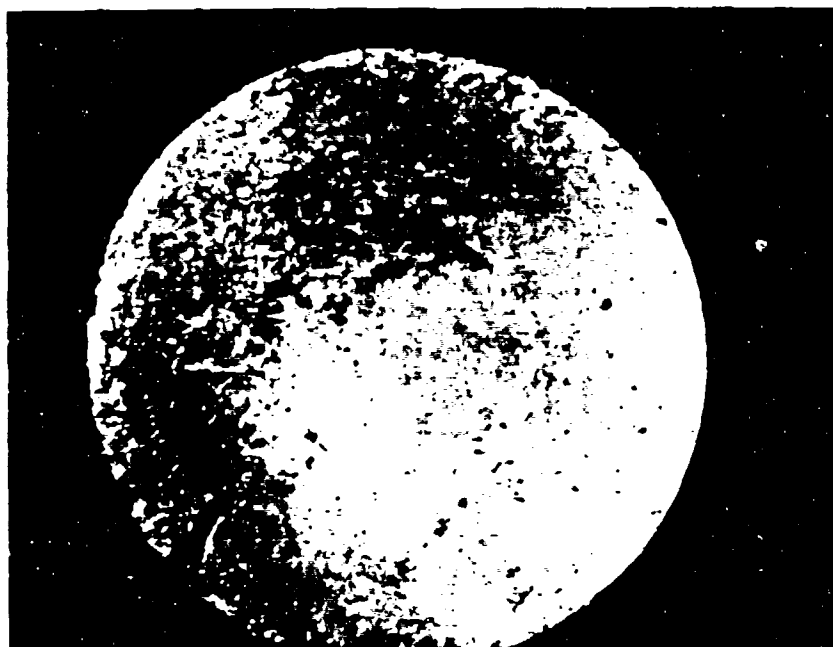


b) Side View

Figure 17. Recovered Composition A-3 Type II Sample Exhibiting Resistance to Cavity Collapse with a 0.38-mm Deep Dimple.

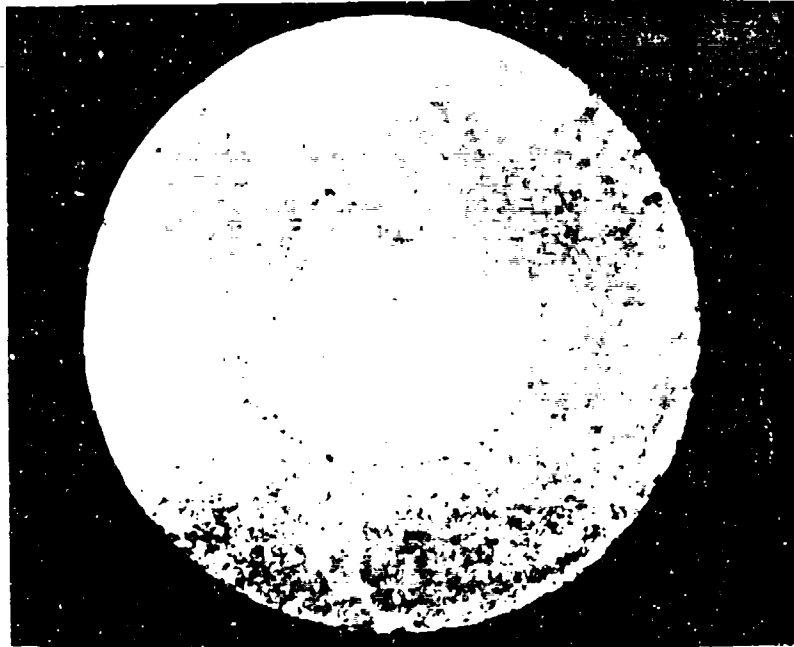


a) 0.38-mm Dimple Depth.

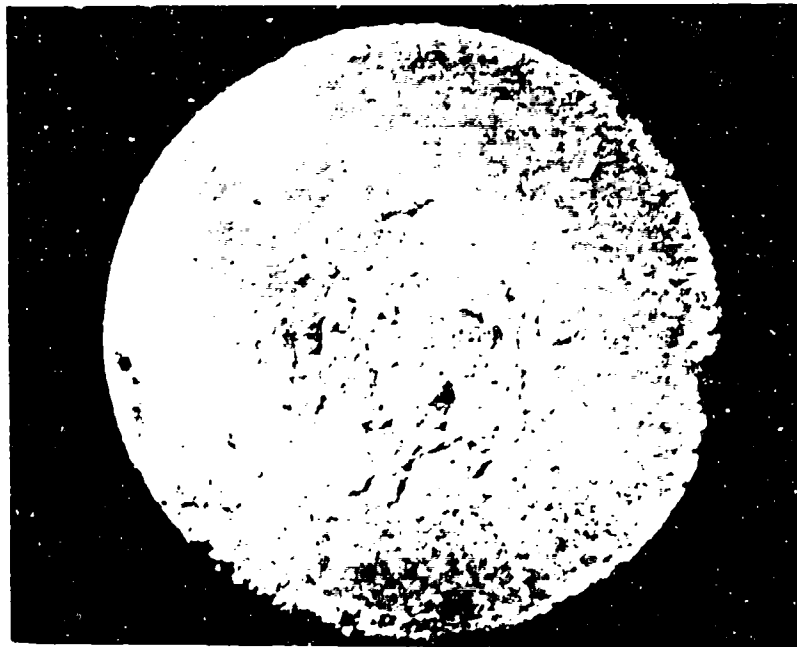


b) 0.76-mm Dimple Depth.

Figure 18. Recovered Composition A-3 Type II Samples.

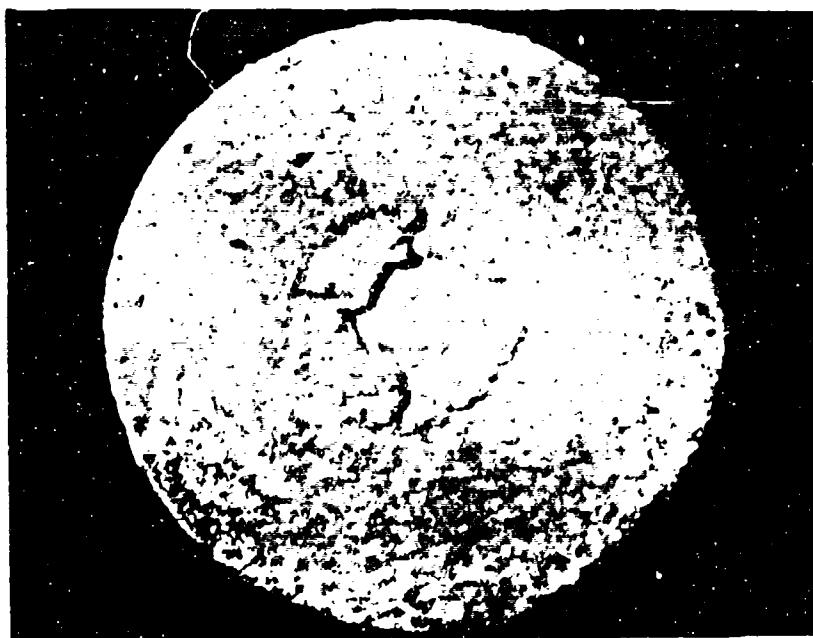


c) 1.14-mm Dimple Depth



d) 1.52-mm Dimple Depth

Figure 18. Recovered Composition A-3 Type II Samples. (Continued)



e) 1.91-mm Dimple Depth

Figure 18. Recovered Composition A-3 Type II Samples. (Continued)

5.5 LX-14. Testing with undimpled LX-14 samples also indicated that free run should be limited to about 20 mm. Again, the number of tests were few but the data segregation is fairly good as shown in Figure 19. However, establishment of a more reliable threshold curve would require some additional data. The maximum tolerable dimple depth is about 0.8 mm and the maximum tolerable free run is about 12 mm. The late ignitions observed occurred on the second strike of the driving piston as evidenced by the manganin gage record (see Figure 20). The reactive response following ignition was very violent. The confinement cylinder was often split into two or more pieces and the bolts holding the gauge block were sometimes broken. For the earlier tests with this explosive, the test section cover was not used and the test assembly was often thrown from its original position causing damage to the activator and attendant equipment. Recovered samples appear to show a transition from bottom-up to radial-inward closure above a depth of about 0.8 mm. These are shown in Figure 21.

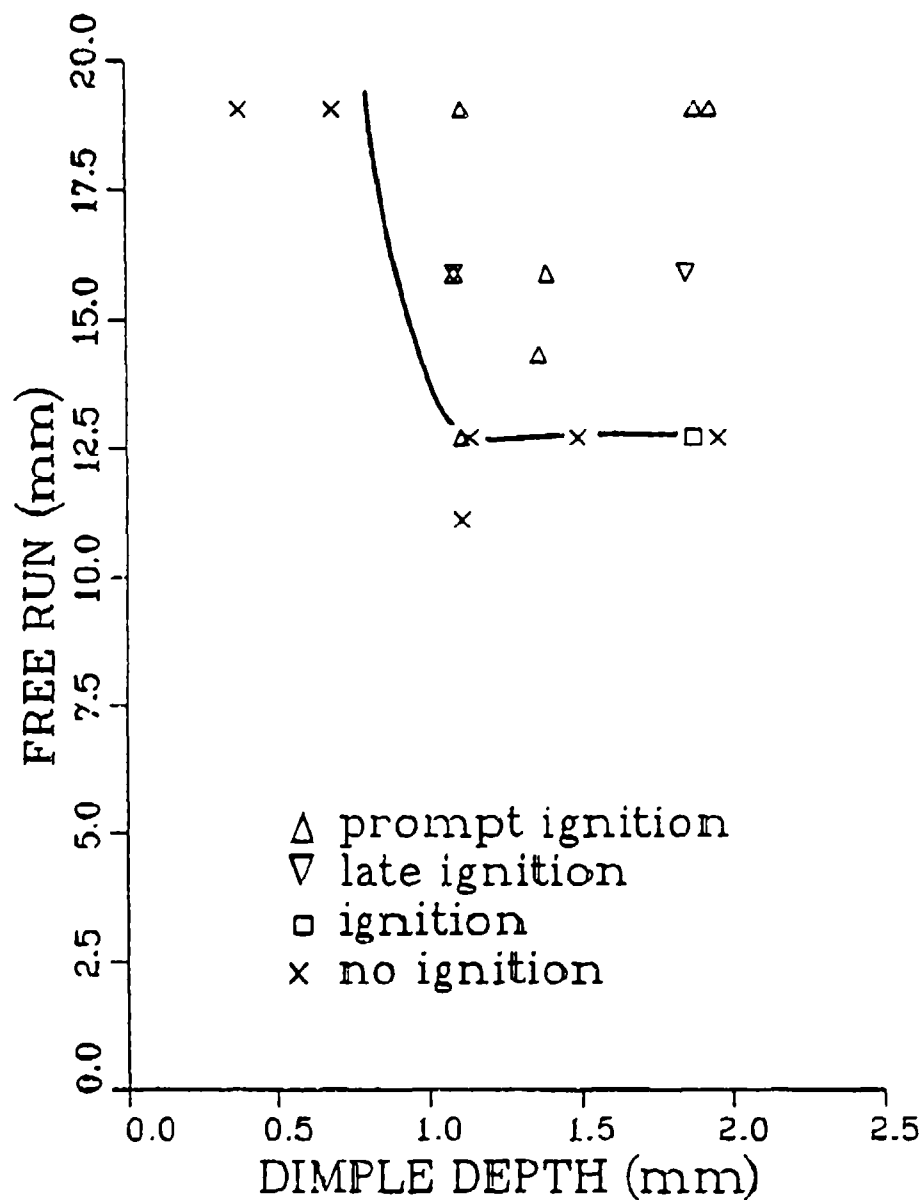


Figure 19. Ignition Threshold for LX-14 in the Dimple Depth - Free Run Plane.

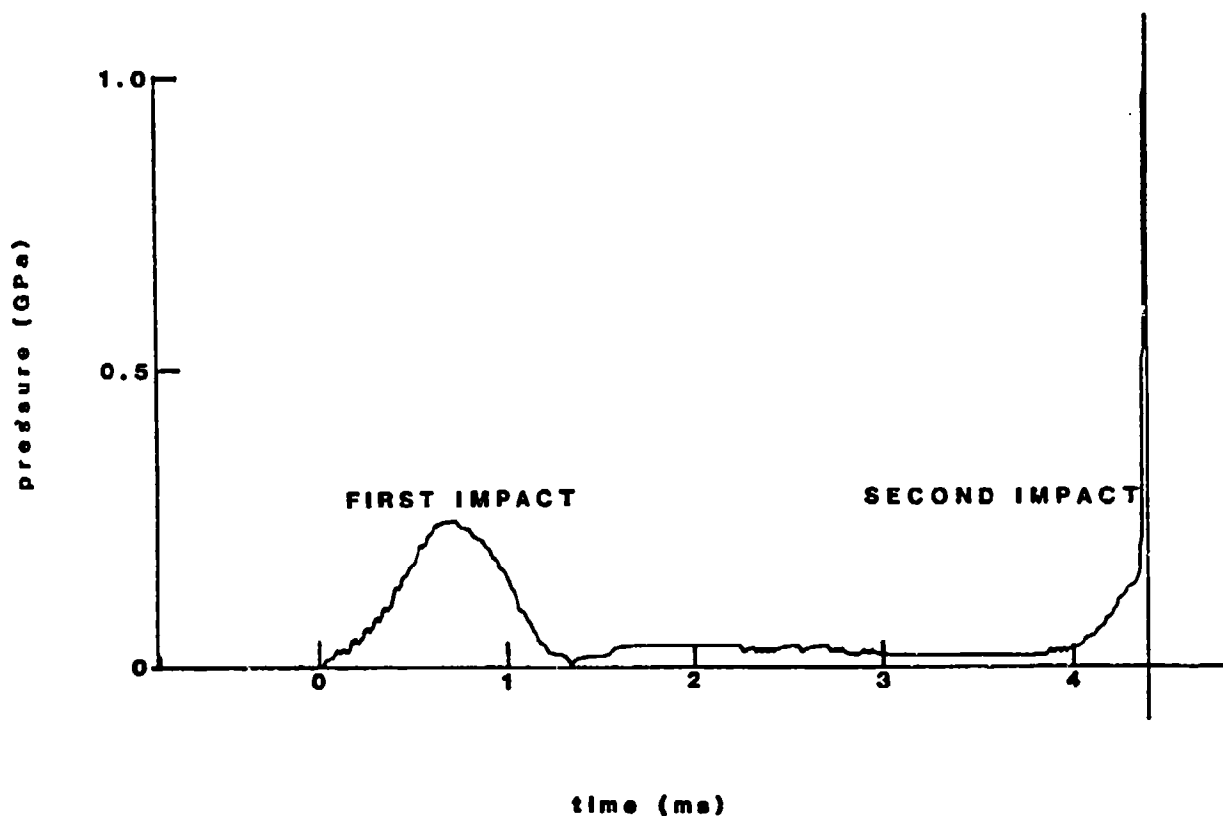
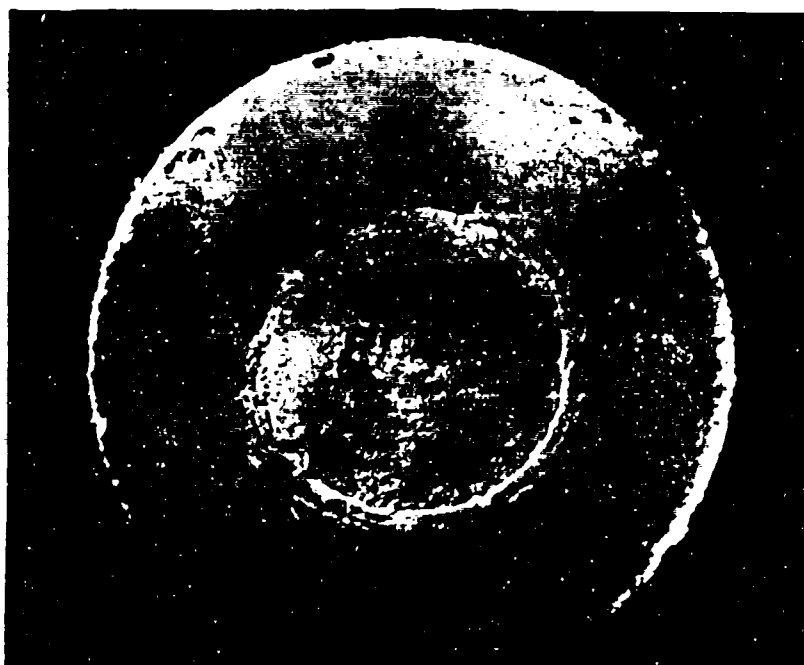


Figure 20. Manganin Gauge Pressure Record Showing Second-Impact Ignition with LX-14.

5.6 PBXW-113. PBXW-113 is a soft rubbery explosive. We found that it responds considerably differently than the other explosives. When no dimples were present, the explosive exhibited an extrusion limit at about 19 mm of free run. However, when dimples of any size were present, testing always produced ignition, even at the shortest possible free run. With one exception, these ignitions occurred very late (often being audibly distinguishable from the stimulus impulse) and were very mild (varying amounts of explosive were usually found to remain). Explosive was often seen to have been sprayed out between the confinement cylinder and the gauge block and could be found in the bolt holes. Test hardware recovered from two such tests are shown in Figures 10a and 22. The results do not lend themselves to the usual presentation in the



a) 0.38-mm Dimple Depth.



b) 0.76-mm Dimple Depth.

Figure 21. Recovered LX-14 Samples.

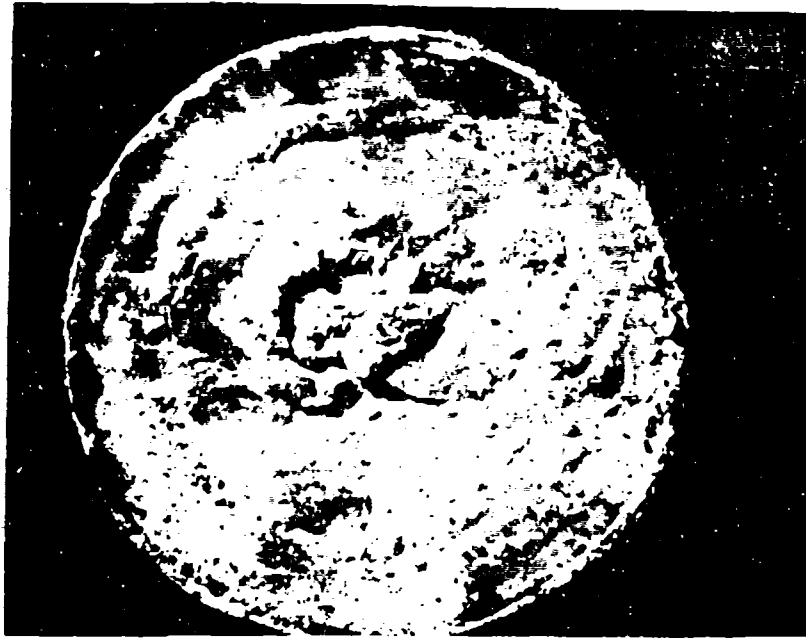


c) 1.14-mm Dimple Depth.



d) 1.52-mm Dimple Depth.

Figure 21. Recovered LX-14 Samples. (Continued)



e) 1.91-mm Dimple Depth

Figure 21. Recovered LX-14 Samples. (Continued)

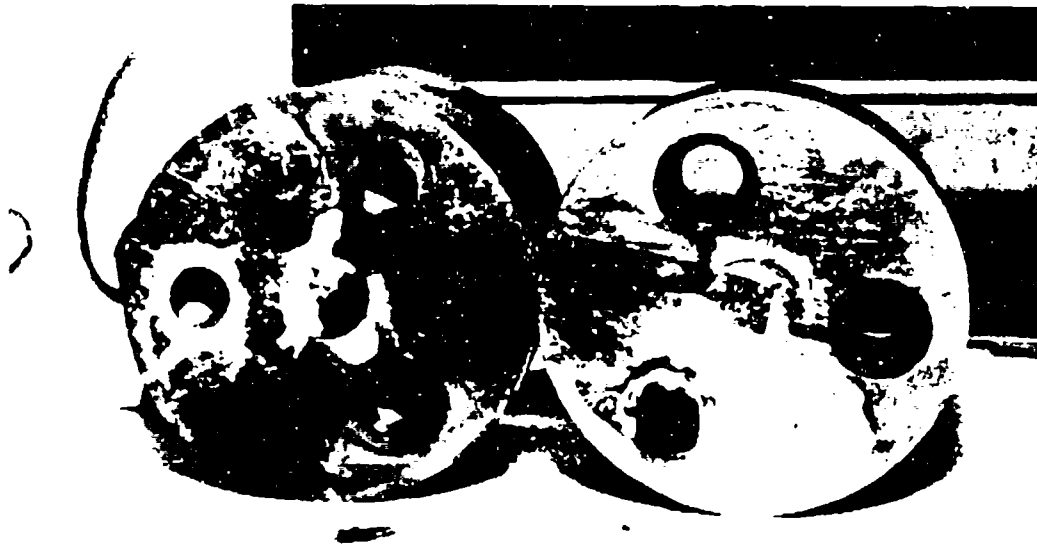


Figure 22. Hardware Recovered from Test With PBXW-113

dimple depth - free run plane. Rather, they are summarized in Table 3, which lists each test. The mild events observed may be a result of the activator's short pulse. The one burn that occurred during the high pressure portion of the pulse was quite violent, splitting the confinement cylinder. During gun launch the pressure may be maintained for a longer time, allowing a more violent burn with this explosive. Since all dimpled samples ignited, the mode of cavity closure could not be assessed.

Table 3. Summary of Results with PBXW-113.

DIMPLE DEPTH (mm)	FREE RUN (mm)	IGNITION?	EXPLOSIVE REMAINING
no dimple	12.7	no	all
no dimple	12.7	no	all
no dimple	15.9	no	all
no dimple	19.1	no	all
no dimple	19.1	late	most
no dimple	22.2	late	half
no dimple	22.2	late	most
no dimple	25.4	late	trace
no dimple	25.4	late	trace
0.38	3.2	late	trace
0.38	6.4	late	none
0.38	6.4	late	?
0.38	12.7	late	most
0.76	19.1	late	some
1.14	19.1	late	none
1.91	3.2	late	trace
1.91	9.5	late	?
1.91	12.7	late	?
1.91	19.1	prompt	none
1.91	19.1	late	?

5.7 PBX-0280. Five undimpled samples of PBX-0280 were tested in an attempt to determine the extrusion ignition limit. The results, however, were inconclusive. Delayed ignitions were observed in three tests at free runs of 19, 22 and 25 mm while ignition failures were observed in two tests at free runs of 22 and 25 mm. Dimple tests were then conducted on the remainder of the samples. The dimples in these samples appeared to be machined. Their edges were of only fair quality, showing considerable crumbling. The results of the tests are plotted in the free run - dimple depth plane in Figure 23. Only a few ignition failures (for shallow dimples or low stimulus levels) were observed. In the region of the plane where ignitions appear, considerable mixing of prompt and delayed ignitions were observed. Nonetheless, an ignition threshold can be reasonably well defined. Ignitions frequently resulted in split confinement cylinders. No observations of recovered samples were made.

5.8 PBX-0280/PE. The five undimpled PBX-0280/PE samples were tested at free runs of 19, 22 and 25 mm. Two ignition failures were observed at 19 mm, one prompt ignition and one failure were observed at 22 mm and one prompt ignition was observed at 25 mm. The machined dimples in these samples appeared to be of somewhat better quality than those in the PBX-0280 samples. The results indicate that 19 mm of free run is a safe upper limit in the dimple tests. However, definition of an ignition threshold in the free run - dimple depth plane required tests at free runs in excess of this value as illustrated in Figure 24. Seven tests with dimples shallower than 0.7 mm produced only one delayed ignition at free runs varying between 19 and 25 mm. Only one test at a dimple depth of 1.5 mm yielded an ignition at a free run shorter than 19 mm. The results produce a relatively well-defined ignition threshold. The response of this explosive was a little less violent than that of PBX-0280, producing split cylinders less often. Again, no observations of recovered samples were made.

5.9 Comparison of Sensitivity and Response Violence. The threshold curves for all the explosives (except PBXW-113) are shown together in Figure 25. Many of the explosives exhibit decreasing sensitivity with the deepest dimples used. In most cases, two simple measures of sensitivity for each explosive may be extracted from the data: the maximum tolerable dimple depth (for which no ignition is produced at any free run) and the maximum tolerable free run (for which no ignition is produced at any dimple depth). Table 4 lists the explosives in order of increasing values of the maximum dimple depth tolerated. The reaction violence level is also shown in the table.

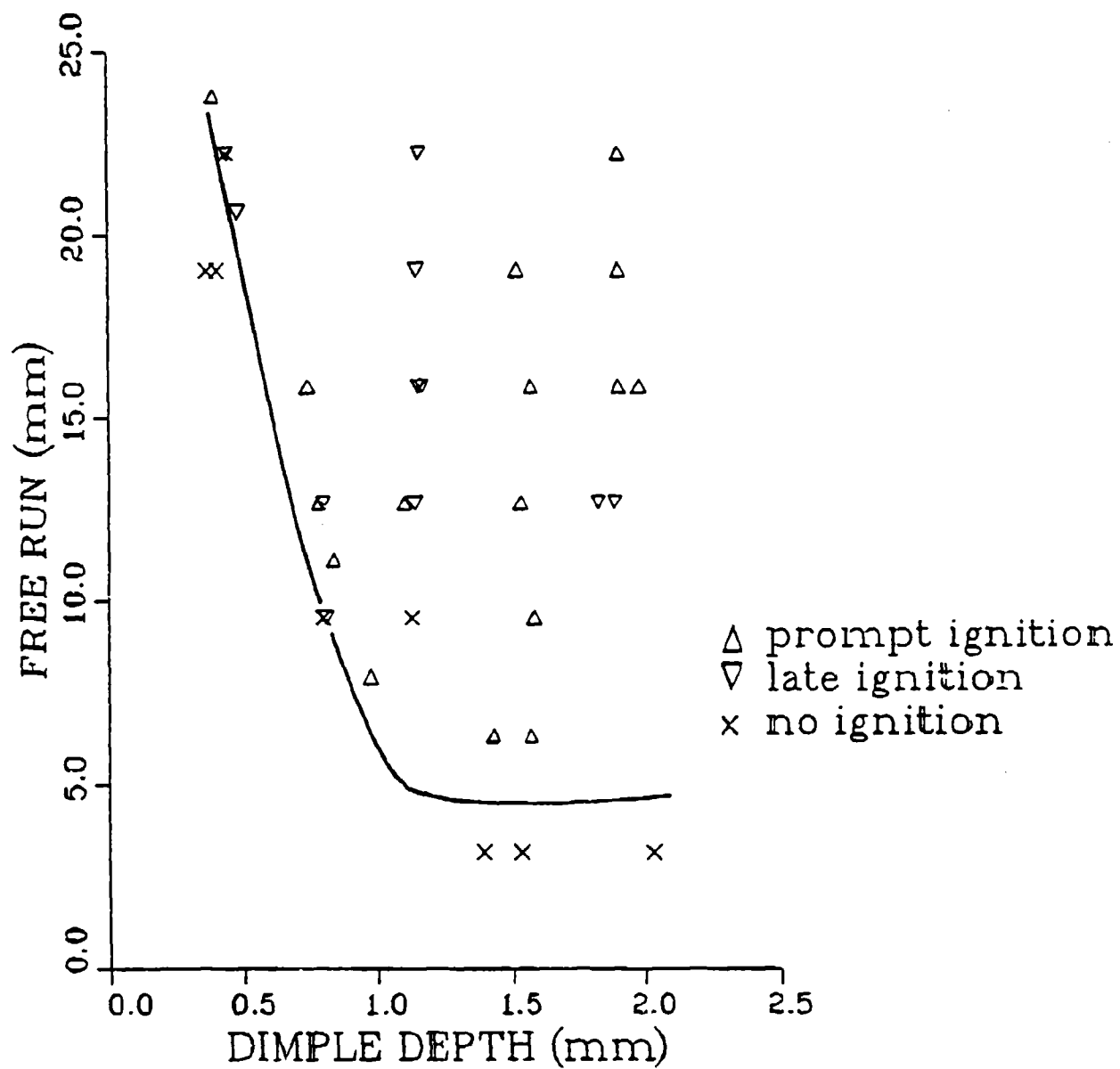


Figure 23. Ignition Threshold for PBX-0280 in the Dimple Depth - Free Run Plane.

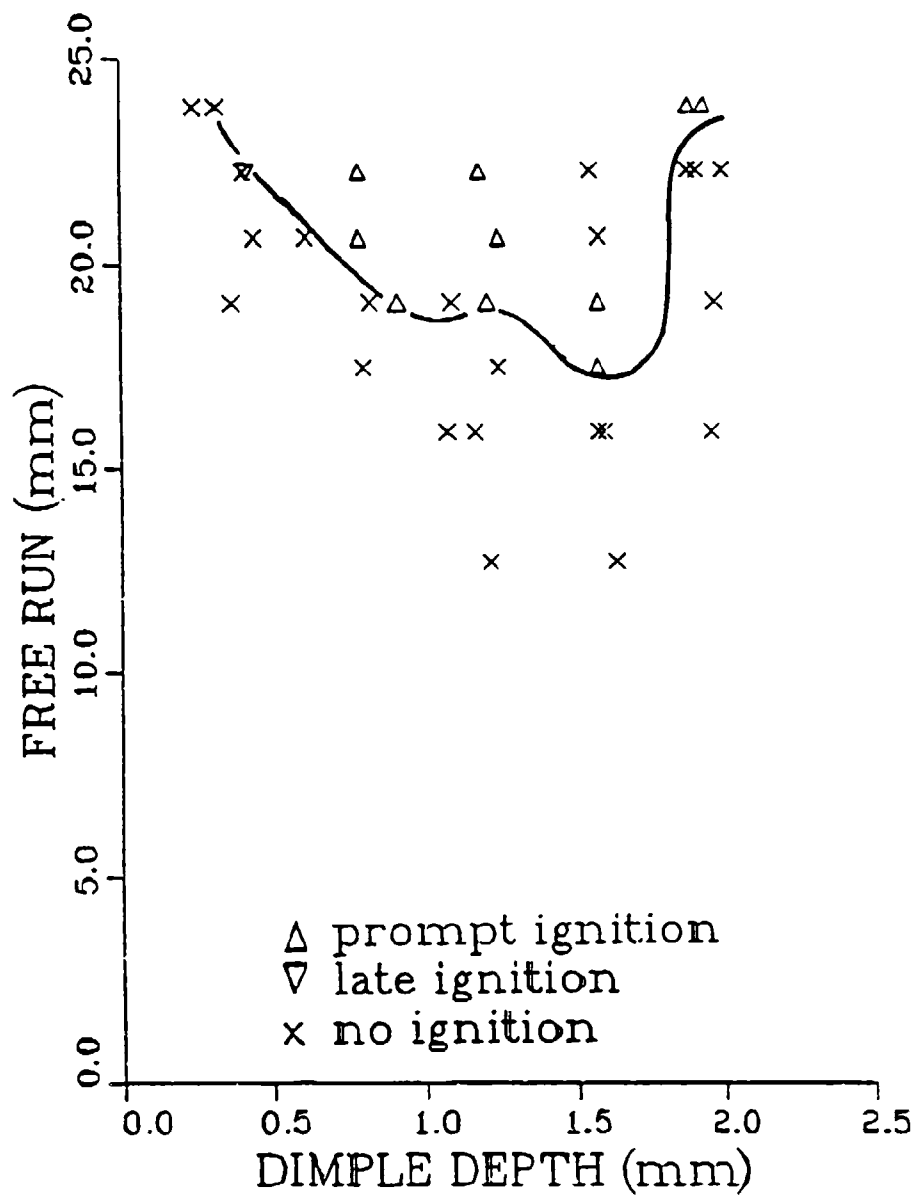


Figure 24. Ignition Threshold for PBX-0280/PE in the Dimple Depth - Free Run Plane.

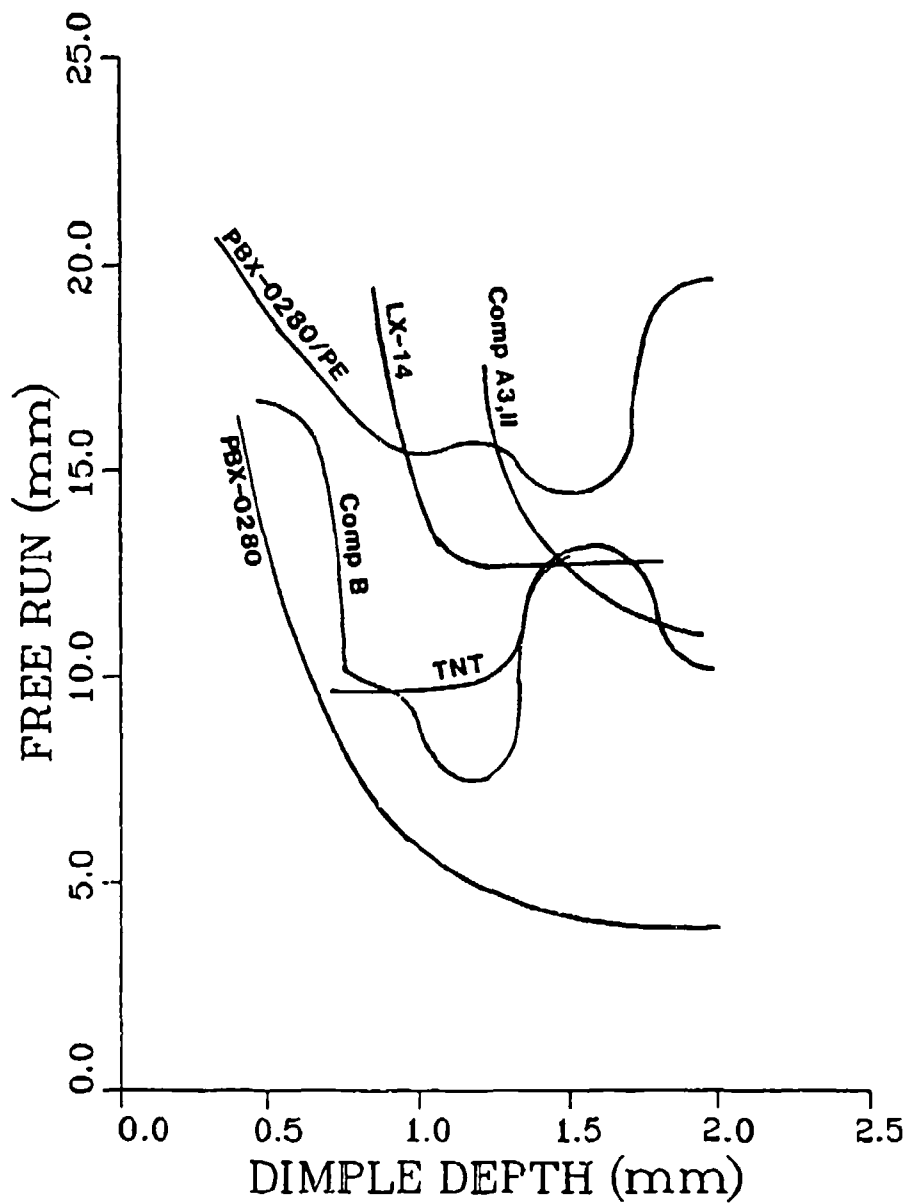


Figure 25. Comparison of Ignition Thresholds in the Dimple Depth - Free Run Plane.

Table 4. Relative Sensitivity of Explosives.

Explosive	Maximum Tolerable		Reaction Violence
	Free Run (mm)	Dimple Depth (mm)	
PBXW-113	0	0.0	1*
PBX-0280	7	0.5	3
Comp B	10	0.5	2,3
TNT	12	0.5?	1,2
PBX-0280/PE	17	0.5*-0.9	3,4
LX-14	12	1.0	4
Comp A3, II	12	1.4	3,4
		* delayed ignition ignored	* violent reaction ignored

The results exhibit some tendency toward an increase in reaction violence with decreasing ignition sensitivity. PBXW-113 is by far the most sensitive in this test. It also produces the mildest response. Comp B exhibits one of the highest sensitivity levels among the brittle explosives and responds violently. Although the data for TNT do not permit definition of a complete ignition threshold, they provide no reason to believe that TNT is less sensitive to ignition than Comp B. This lends support to the interpretation that the higher frequency of premature explosions observed with Comp B filled rounds is due to its higher explosiveness. Comp A3 Type II may be considered the least sensitive explosive tested (based on maximum tolerable dimple depth). It exhibits a moderately high level of response violence. Its maximum tolerable dimple depth is considerably greater than that for Comp B but no decrease in sensitivity with deeper dimples is observed leading to an apparent crossover of the thresholds for deep cavities. LX-14 exhibits a sensitivity intermediate between those of Comp B and Comp A-3 Type II and reacts very violently. Its threshold also crosses over that of Comp A-3, Type II, for deep dimples. The sensitivity of PBX-0280 is generally greater than that of Comp B. It ignites at lower stimulus levels and tolerates roughly the same dimple depth as Comp B. PBX-0280/PE, on the other hand, appears quite insensitive in terms of the stimulus level tolerated. Although it was observed to ignite with relatively shallow dimples, this was at very high stimulus levels and may have been due to extrusion. The difference in sensitivity between these two explosives is remarkable since they

both contain ninety-five percent RDX and were tested at almost exactly the same percentage of theoretical maximum density. The principal differences are the binder material and the particle size of the RDX used. The less sensitive explosive uses polyethylene as a binder and much coarser RDX.

Our results can be explained most satisfactorily in terms of each explosive's tendency to deconsolidate, or break up into small particles, during cavity collapse. Evidence of deconsolidation is apparent in samples which failed to ignite as shown in Figures 12, 13, 14, 18 and 21. Such break-up produces competing effects on the sensitivity to ignition. It desensitizes by presenting greater explosive surface area to a limited quantity of heated air. This is the same mechanism that accounts for the decreased sensitivity previously observed at low pressing density. At the same time, deconsolidation sensitizes by raising the explosive-air interface temperature for particles that are sufficiently small compared to the heated layer thickness. Only one of the explosives tested is made with a significant number of particles which are smaller than the 50 μm size suggested by our earlier analysis ^(1,3). Thus, in most cases, it appears that the desensitizing effect dominates. In addition, the increased surface area manifests itself in a more violent response when ignition does occur. The results are, of course, influenced by each explosive's intrinsic sensitivity to pure thermal stimulus and the amount of energy released in decomposition.

The mechanical properties of PBXW-113 render it the most resistant to deconsolidation and it shows the greatest sensitivity and the lowest reaction violence. TNT might be expected to break up less readily than the other brittle explosives because it is a single phase cast material. It exhibits a relatively high ignition sensitivity and is the second lowest in reaction violence. Comp B, as a multiphase cast explosive, is somewhat higher in reaction violence and has about the same sensitivity as TNT. Here, the slower energy release of TNT is also a factor. The remaining explosives are multiphase pressed materials and (with the exception of PBX-0280) exhibit lower sensitivities and higher reaction violence levels. The order of sensitivity of PBX-0280 and PBX-0280/PE are not consistent with the dominance of the desensitizing effect. However, the more sensitive PBX-0280 contains class 5 RDX (virtually all particles less than 50 μm) and class 7 RDX. It can be expected to produce a significant quantity of very small particles upon deconsolidation. This might explain its high sensitivity. The binder difference could also have some effect on sensitivity by influencing the explosive's mechanical properties and, in turn, the degree of deconsolidation and the mode of cavity collapse.

6. CONCLUSIONS

The path toward more premature-resistant explosives is not clear. Velicky, Voigt and Voreck ⁽¹⁹⁾ have suggested that an explosive's mechanical strength should be increased to reduce the probability of collapse of casting flaws. However, it seems likely that this will have little effect on cavities large enough to present a problem since the launch acceleration environment appears to produce stresses well above those required to collapse larger cavities. Because of the importance of the gas pressurization rate, increasing mechanical strength might even have a negative effect. Delaying cavity collapse until higher stress levels have been reached could increase the pressurization rate. Cavities in a softened material, meanwhile, might collapse slowly during the very early portion of launch, thus resisting ignition. On the other hand, they might better trap hot air, thus promoting ignition. In the latter case, the low ignited surface area can be expected to yield low initial reaction rates which may sufficiently delay any violent response. Approaches which reduce the incidence of flaws in explosive fills, reduce the ignitability of the explosive or retard the burning response of the explosive are, of course, desirable. Because of the complexity of the issues involved, characterization of explosives through testing is the only available approach to discovering premature resistant formulations.

Our observations indicate that field experience cannot be correlated with the results of ignition sensitivity tests. Thus, both ignitability and explosiveness should be considered in assessing an explosive's resistance to launch-induced explosion. In the controversy between brittle and soft explosives, our ignition sensitivity results are biased in favor the brittle materials. For this reason, we do not believe that explosives should be rejected on the basis of exhibiting high ignition sensitivity in the activator unless the reaction violence levels are also high. The activator may be limited in its ability to appropriately measure explosiveness since it generates a considerably shorter pulse than that produced in the launch environment. This could inhibit violent reaction for explosives which do not burn rapidly either because insufficient surface area is produced during cavity collapse or because of relatively slow chemical kinetics. Clearly, our approach tells only part of the story since the applied stimulus level in the activator is partially independent of explosive mechanical properties and the testing may not reflect all the ways in which the mechanical properties influence the stimulus amplification mechanism. In spite of all this, the activator, when used with care, remains the best available tool for assessing an explosives resistance to launch-induced premature explosions.

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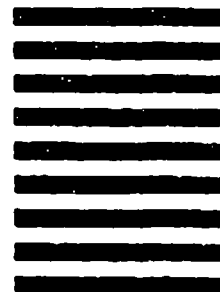


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